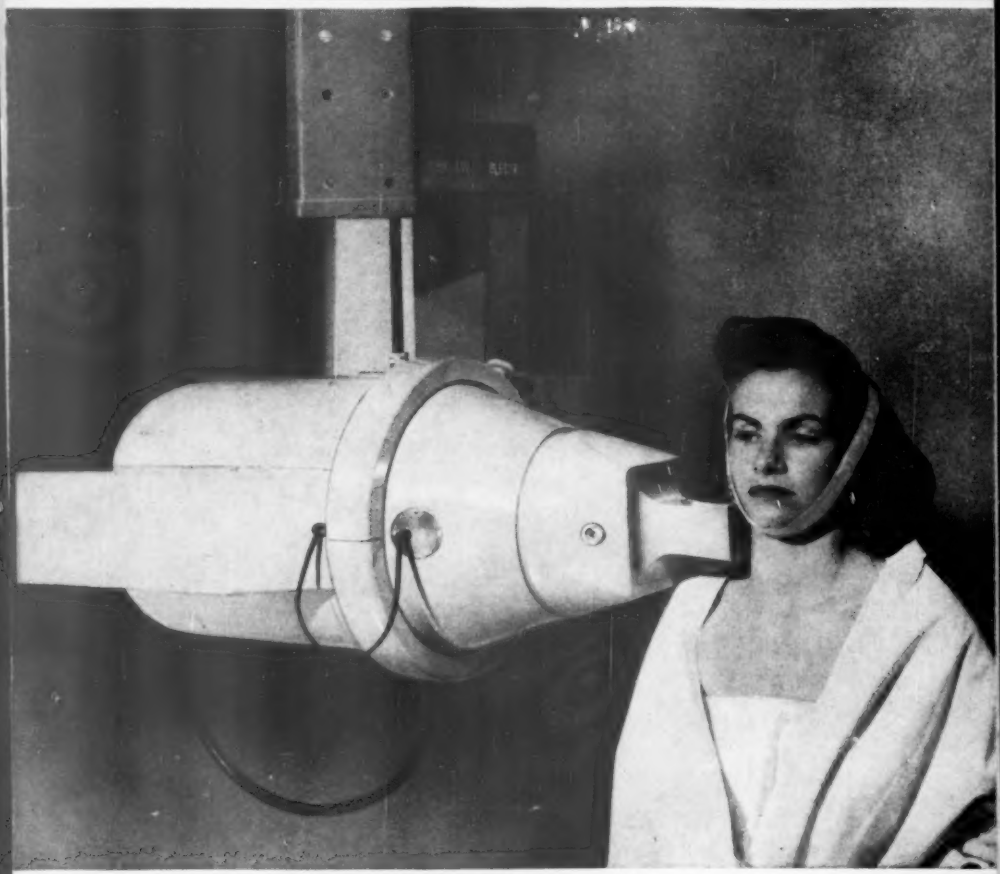
NUCLEONICS

TECHNIQUES AND APPLICATIONS OF NUCLEAR SCIENCE AND ENGINEERING

September, 1951



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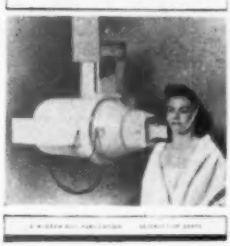

THE COVER shows the Co^{60} medical therapy unit being built by General Electric Co. for use at the M. D. Anderson Hospital, Houston, Texas. The unit, which will receive preliminary testing at Oak Ridge Institute of Nuclear Studies, will use a 1,000-curie source, to be made up of four 1-in² cobalt wafers now being irradiated in Canada's Chalk River reactor

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NUCLEONICS

Breeder Reactor

As this is being written, the first reactor in the world designed to produce more fissionable material than it consumes may be going into operation. This is AEC's $3,300,000 experimental breeder reactor (EBR) just completed at the Reactor Testing Station in Idaho.

The success of this reactor will depend substantially upon how efficiently it can put to use the excess neutrons (those not necessary to maintain the chain reaction) which are produced in fission. Other important factors are the rate at which fuel can be burned, the length of time fuel elements will stand up, and the total amount of fuel and fertile material tied up in the reactor and in various stages of processing.

If breeding works, its future will be determined in part by economic considerations. Since the primary purpose of a breeder is to increase our supply of fissionable material, its cost may have to be compared with the cost of developing low-grade uranium deposits. However, although EBR is using uranium-238 as the fertile material (that which can be transformed into a fissionable substance), if thorium-232 can be used instead, scarcity of uranium will not be a problem since thorium is in much greater supply.

This first of the new generation of reactors planned since the end of the war has the makings of an important milestone. We have our fingers crossed in hopes that it lives up to its name and "breeds."

Progress in Waste Disposal

As more reactors are built, problems of disposal of liquid radioactive wastes increase. Where wastes must be stored, many expensive, shielded, leak-proof tanks are necessary. After several years of this, costs mount and space

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begins to run out. So, for the past several years, AEC has conducted a research program to develop methods for concentrating these wastes.

Brookhaven National Laboratory recently reported the development of a waste evaporation process which would cost $0.05 per gallon. This compares very favorably with a cost of $0.27 per gallon for above-ground tank storage and $1.05 per gallon for below-ground tank storage.

Last year, AEC predicted that the installation of the Brookhaven waste concentration plant would extend the storage capacity of the waste field by 4 to 6 years, or about double its normal useful life as a wholly liquid waste facility.

Different from most other industries, the atomic energy industry has shown considerable foresight in anticipating its waste problems. This waste concentration development is further evidence of this. What with extensive efforts now being carried out to recover unused uranium from reactor wastes and to find applications for the fission products, we may yet reach the point where we have no unused wastes.

The Times We Live In

The Tenth Semiannual Report of the AEC shows the signs of our times in two ways:

1. The report does not cover any part of the atomic energy program in detail.

This appears to be the result of the pressure of other higher priority tasks and the lack of subject matter easily describable in the open literature.

Each of AEC's four preceding semiannual reports was devoted for the most part to a detailed description of one phase of the program. Such things

(Continued on page 90)

Random Notes

• *As with the income tax collector, anniversaries come around every year. This month, we enter our fifth year of publication.*

We are satisfied with the progress we have been making. And we think our readers are. Evidence of acceptance has come in the form of an increasing number of unsolicited manuscripts and in a gradual increase in circulation.

Rather than take this occasion to look at the past, we're going to look into the future of one segment of the job we're doing—the "Cross Sections" (C. S.) Dept. (p. 76). We have hopes of developing this section into one of the most practical in the magazine.

We established it a little more than a year ago because of a dual need: (1) for a medium of quick publication and (2) for a forum for brief technique notes. The title "Cross Sections" was selected because of its Webster definition rather than its nuclear origin. We wanted a name which would cover the broad scope envisaged.

The department this month provides an excellent illustration of the various ways in which material is gathered.

(Continued on page 90)

Portable ALPHA SURVEY METER

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Portable Alpha Survey Meter—Model #4SN10A2

SPECIFICATIONS

Range: 0-10,000 d/m/150 cm^2

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Detector: Air proportional counting chamber, integral with case.

Accuracy: ± 10% of indicated reading

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Alpha window: Less than 2. mg/cm^2 (non permeable to moisture)

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Humidity: 0-95% relative humidity (chamber sealed against moisture)

A "must" for anyone handling radium or other alpha emitting material. Thoroughly reliable even in high humidity. A multiple wire counter, this compact, portable unit was originally developed from work done with AEC and the U. S. Navy (AEC Catalog No. STC-2C; Navy Type AN/PDR10A). For informative bulletin, write: *General Electric Company, Section 661, Electronics Park, Syracuse, N.Y.*

G-E PRECISION UNITS

Binary Scaler—Type 4SN1A3. Provides a scale of 2 in self-contained plug-in unit.

Radiation Monitor 4SN11A2. Self-charging. Measures milliroentgens of gamma radiation.

GENERAL ELECTRIC

Photographic X- and Gamma-Ray Dosimetry*

A four-film dosimeter having an accuracy of ±20% in the ranges 1 to 10,000 r and 115 kev to 10 Mev is described. It is not necessary to know the radiation quality. Methods for choosing emulsions and absorbers are discussed in full

By MARGARETE EHRLICH and STEPHEN H. FITCH†

Radiation Physics Laboratory, National Bureau of Standards
Washington, D. C.

PHOTOGRAPHIC EMULSIONS lend themselves well to absolute dosage determinations over large ranges of radiation flux. This is because their response to X- and gamma radiation is independent of radiation flux for intensity ratios of at least 1:10,000 (*1*, *2*).

Radiation monitoring by means of photographic emulsions is inexpensive, rugged, and sensitive. Its main drawbacks are the necessity for time-consuming emulsion processing and the dependence of emulsion sensitivity on the energy of the exposing radiation.

Since there are indications that, in the near future, it will be possible to overcome the drawback of elaborate processing, it seems certain that photographic dosimetry will remain a valuable aid in industrial safety and casualty monitoring as well as in civilian defense measures. The effort of decreasing the energy dependence of photographic dosimeters is, therefore, of considerable importance.

This paper discusses the general experimental and theoretical considerations involved in the design of a photographic-film dosimeter whose response is independent of the secondary electrons that arise in adjacent structures and whose energy dependence is reduced materially by metallic absorbers which tend to counteract the high sensitivity of film emulsions for low-energy radiation.

These considerations are then applied to the design of a dosimeter with a useful exposure range of 1–10,000 r. This range allows a dosage interpretation within accuracy limits of ±20% for X- and gamma-ray energies from 115 kev up to about 10 Mev, without any further knowledge of radiation quality.

While this paper deals primarily with X- and gamma-ray dosimetry by means of photographic emulsions, an effort is made to show in detail how one studies energy dependence of X- and gamma-ray dosimeters in general, and how one may compensate for this dependence.

Reduction of Energy Dependence

The response of all presently available photographic emulsions varies with energy in the general proximity of the absorption edges of silver and bromine and shows peaks in these regions. This complicates the use of photographic emulsions for X- and gamma-ray dosimetry over wide quantum-energy ranges (*3*, *4*). Thus, whenever the radiation incident on a film dosimeter has components in the quantum-energy range of these absorption edges,

* Based on work performed under Contract 73-PHIB-50-6 between the Signal Corps and the Radiation Laboratory of the National Bureau of Standards, Washington, D. C.

† PRESENT ADDRESS: Naval Radiological Defense Laboratory, San Francisco Naval Shipyard, San Francisco, California.

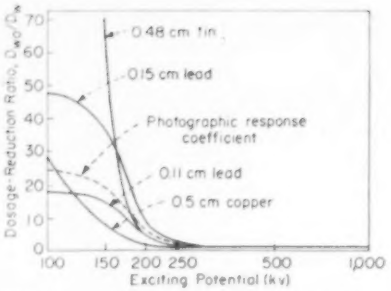

FIG. 1. Reduction of X-ray dosage by means of metallic absorbers

it is impossible to interpret film densities in terms of radiation dosage as measured in roentgens, unless the radiation spectrum is known. Various attempts have been made to by-pass this difficulty and to design film meters which would be useful for dosage determinations of radiation of unknown quality.

Tochilin *et al.* (*5*), Baker and Silverman (*6*), and other authors have suggested film badges in which different metallic absorbers are used side by side in contact with the film packet. The film-density readings are interpreted with the aid of tables relating the ratios of densities under the different absorbers to the dosage in roentgens received by the film. This method seems cumbersome and inaccurate, especially because of the difficulty in avoiding scattering effects resulting from absorbing materials close to the film packet.

Earlier, Pardue *et al.* (*7*), and Deal and Day (*8*), attempted to compensate for the film response peak by introducing a thin layer of cadmium over the film surface. Pardue and his coworkers experimentally determined the thickness of the cadmium shield for the particular films under consideration. Deal and Day used the same thickness of cadmium in making their calibration of the Dupont 552 experimental film packet.

The work carried out at the National Bureau of Standards was based on the same assumption as was Pardue's and Deal's, namely, that it was possible to make the film response independent of radiation quality by means of metallic absorbers covering the entire emulsion surface. The effect of different metallic absorbers was calculated and the required thicknesses were determined by a graphical method. The results were checked experimentally.

Since the photographic effect is determined to a considerable extent by the absorption of X-rays in silver bromide, a photographic-sensitivity-vs-energy curve should resemble, in its trend, an absorption curve in this material.

A typical photographic response curve is shown in Fig. 1. The ordinate represents the ratio of the dosage in roentgens needed to produce a given photographic density in the million-volt range, where the film response is energy independent, to the dosage needed to produce the same density at a specified low exciting potential. This ratio is called the photographic response coefficient. On the same graph are plotted the ratios of the X-ray dosage in the absence of an absorber, D_{wo}, to the corresponding dosage behind the absorber, D_w, for different values of the exciting potential and for different absorbers.

If the curve of D_{wo}/D_w for any absorber, or combination of absorbers, matches the photographic response curve, the reduction in dosage brought about by these absorbers when placed in front of a photographic film will just compensate for the increase in the response coefficient of the film emulsion. The net photographic response is then expected to be energy independent.

It will be shown in the next section how the approximate values of the ratios D_{wo}/D_w can be determined without extensive experimentation. The results obtained in this way are then

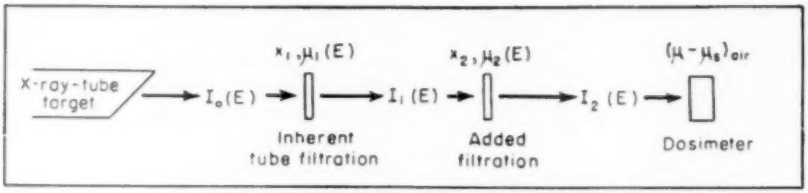

FIG. 2. Path followed by the X-radiation

applied to the selection of an absorber of the desired characteristics.

Modification of X-ray spectra. The technique for the evaluation of different filter combinations is based on the calculations leading to the dosage ratios, D_{w_0}/D_w.

The calculations were carried out for heterochromatic X-radiation from a constant-potential X-ray machine. This type of source was actually used in the dosimeter calibration for lack of monochromatic sources in the particular energy regions. The width of the energy bands was made as narrow as conditions permitted.

The detailed spectrum of the X-radiation emerging from an X-ray-tube target is generally unknown. It is, however, possible to gain valuable information regarding the spectral modification and dosage reduction caused by absorption under the assumption of a simple, idealized spectral distribution.

According to Kramers' theoretical formula (*9*), the spectral energy between E and $E + dE$ emitted per electron impact is given by

$$I(E)dE = -C(E - C_0)\,dE$$

which represents a straight line with the constant slope $-C$ in an intensity-vs-energy plot. This idealization is not unrealistic, as shown by good agreement with the empirical formula developed by Kulenkampff (*10*).

Figure 2 is a schematic representation of the path of the X-radiation from its origin in the target, through the different filter materials, to its absorption in a dosimeter. One should actually introduce in this diagram another block, representing the filtration by the air intervening between the tube and the dosimeter. However, the filtration by air is negligible in the present example.

If $I_0(E)dE$ is the spectral intensity distribution in the photon-energy interval dE, as represented by Kramers' formula, and if $I_1(E)dE$ is the intensity distribution in the same interval after its attenuation by the inherent tube filtration, then

$$I_1(E)dE = I_0(E)e^{-\mu_1(E)x_1}\,dE$$

where $\mu_1(E)$ is the linear absorption coefficient; x_1 is the thickness, in centimeters, of the equivalent X-ray-tube filter, as given by the manufacturer. The quantity $I_2(E)dE$ represents the spectral intensity distribution in the interval dE after passage of the X-ray beam through the added filtration of thickness x_2 and linear absorption coefficient $\mu_2(E)$. Thus

$$I_2(E)dE = I_1(E)e^{-\mu_2(E)x_2}dE$$

If an X-ray beam, characterized by the spectrum $I_2(E)$, falls on a free-air ionization chamber, each portion, δE, of the spectrum contributes to the dosage, D, as measured in roentgens, an amount δD proportional to the fraction of the beam intensity within δE that is absorbed by the air of the ionization chamber. Below the pair-production threshold, this fraction is given by the intensity, $I_2(E)\delta E$, multiplied by the corresponding air absorption coefficient, $[\mu(E) - \mu_s(E)]_{air}$. Thus the fraction

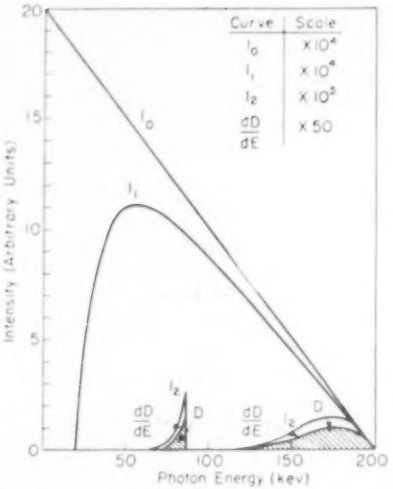

FIG. 3. Changes of X-ray spectrum by filtration

$$\delta D \propto [\mu(E) - \mu_s(E)]_{air} I_2(E) \delta E$$

represents the fraction of the primary beam intensity removed from the beam by Compton electrons.*

Thus, the total dosage is expressed in the form

$$D \propto \int_0^{E_0} I_2(E)[\mu(E) - \mu_s(E)]_{air} dE$$

Figure 3 shows the progressive spectral changes computed in this manner for an X-ray beam generated at a 200-kv exciting potential passing through an inherent filtration equivalent to 3 mm of aluminum and through an initial beam filter of 1.96 mm of lead. For the computations, C was set equal to 1,000 units of the ratio of spectral intensity to photon energy. The spectral intensity distributions $I_0(E)$, $I_1(E)$, and $I_2(E)$ are plotted in the same arbitrary units, while the curve for the differential dosage contribution dD/dE is on a scale a thousand times larger. The inherent filtration is seen to cut off the softest radiation. The lead filtration suppresses the lower energies more strongly than the higher ones, except in the portion of the spectrum immediately below the K-absorption edge. The dD/dE curve parallels roughly the $I_2(E)$ curve because $[\mu(E) - \mu_s(E)]_{air}$ is fairly constant in the energy range in which $I_2(E)$ is appreciably different from zero.† The total dosage, D, is represented by the area under the dD/dE curve; it was evaluated planimetrically.

Any additional absorber between the lead filter and the dosimeter further reduces the dosage, and hardens the X-ray beam as well. Therefore, to reduce the spectral components of the radiation to which the film emulsions are selectively responsive, metallic absorbers are used in immediate contact with the measuring device. A tentative method was developed for the evaluation of their effective absorption by means of a correction, $\mu_{sf}(E)$, to the linear absorption coefficient, $\mu(E)$. The contribution to the total absorption coefficient made by the degraded Compton photons scattered in the forward direction is represented by $\mu_{sf}(E)$. These photons, to a large extent, are not absorbed in the filters and, as a first approximation, $\mu_{sf}(E)$ is subtracted from the total absorption coefficient. The total dosage is then given by

$$D \propto \int_0^{E_0} I_2(E)[\mu(E) - \mu_s(E)]_{air} \times e^{-[\mu(E) - \mu_{sf}(E)]_{abs} x_{abs}} dE$$

Calculations were made for various thicknesses of lead and tin. Sample data of the differential dosages, dD/dE, computed for 250 kev are plotted in Figs. 4 and 5. The curve representing the differential dosages measured with-

* In the definition of the roentgen, the contribution of scattered photons to absorption is neglected.

† At energies below 50 kev, the absorption coefficient, $[\mu(E) - \mu_s(E)]_{air}$, rises sharply. This causes a marked rise of the dD/dE curve below 50 kev for X-ray spectra with strong components in this energy range, and thus causes a distortion of the total dosage measurements.

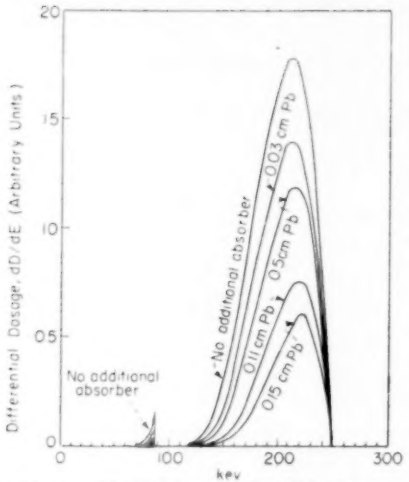

FIG. 4. Modification of the 250-kev radiation spectrum by lead absorbers

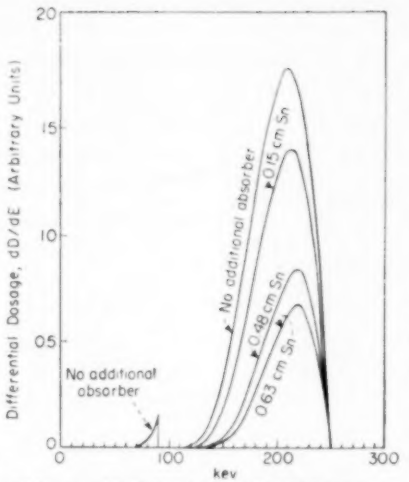

FIG. 5. Modification of the 250-kev radiation spectrum by tin absorbers

out any additional absorber is included on both graphs for reference.

Similar calculations were carried out on both lead and tin for 100-, 150-, and 200-kv exciting potentials. A comparison between the tin and lead curves shows clearly that below the K edge for lead the absorption by tin exceeds the absorption by lead, while above the K edge lead is the more effective of the two.

Planimetry of the areas under each curve yields the total dosages measured behind the absorbers. The dosage-reduction ratios, D_{wo}/D_w, were calculated from the total dosages. They are plotted against absorber thickness in Fig. 6.

To determine which absorbers would best remove the energy dependence of a photographic emulsion, the particular thickness of each absorber is determined such that the dosage-reduction ratio, D_{wo}/D_w, is equal to the response coefficient of the emulsion. This could be done by matching the photographic-response curve and the reduction-ratio curves as indicated in Fig. 1. Instead of matching the curves visually, the required absorber thicknesses were taken directly from the dosage-reduction-ratio-vs-thickness plot of Fig. 6.

Design of the Dosimeter

In the following, the ideas developed in the previous section will be applied to the design of a film dosimeter covering the exposure range from 1 to 10,000 roentgens. The same pattern may be followed for work with any photographic emulsion.

Selection of emulsions. Sixteen different film emulsions were calibrated over their entire useful exposure range with X-radiation of 1.4-Mv exciting potential having a half-value layer of 10.4 mm of tin and an effective energy of approximately 600 kev. In this energy region, the response of the photographic emulsions is essentially independent of the quantum energy of the incident radiation. The X-ray intensities were measured with a Victoreen roentgen meter with walls of electronic equilibrium thickness. The exposed films were developed in East-

TABLE 1

Photographic Response Coefficients of the Four Selected Emulsions

Exciting potential (kv)	*Half-value layer (mm Sn)*	*Response coefficients*			
		Dupont 510	*Dupont 605*	*Eastman positive 5302*	*Eastman spectroscopic 548-0 (double coat)*
500–1,400	6.4–11.3	1	1	1	1
250	3.64	2.0	1.55	1.17	2.00
200	2.19	2.8	2.05	2.40	3.33
150	1.01	5.5	4.9	3.33	6.56
100	0.33	23.6	19.0	>33.34	30.8
50	0.08	27.5	29.0		

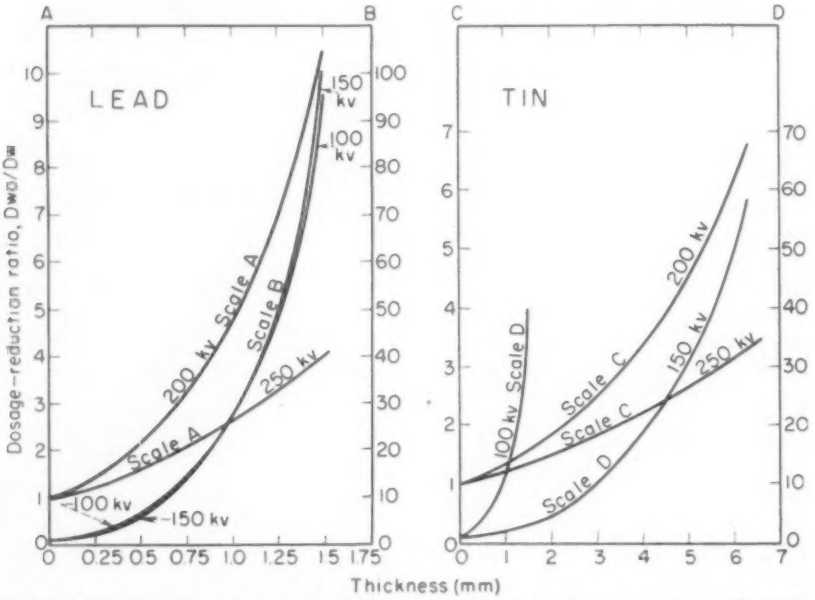

FIG. 6. Determination of absorber thickness required for reduction of energy dependence of emulsions

man X-ray developer for five minutes at 20 ± 0.1° C.

Figure 7 shows the calibration results graphically. The indicated accuracies were obtained by calculating the percentage of the total exposure in roentgens corresponding to either a density variation of 5%, as limited by darkroom procedures, or 0.02 density units, as limited by the accuracy of the densitometer, whichever was larger. This variation was accepted as the inherent inaccuracy of the calibration procedure.

The Eastman spectroscopic film 548-0, double-coat, is the only film which covers the dosage range 500–

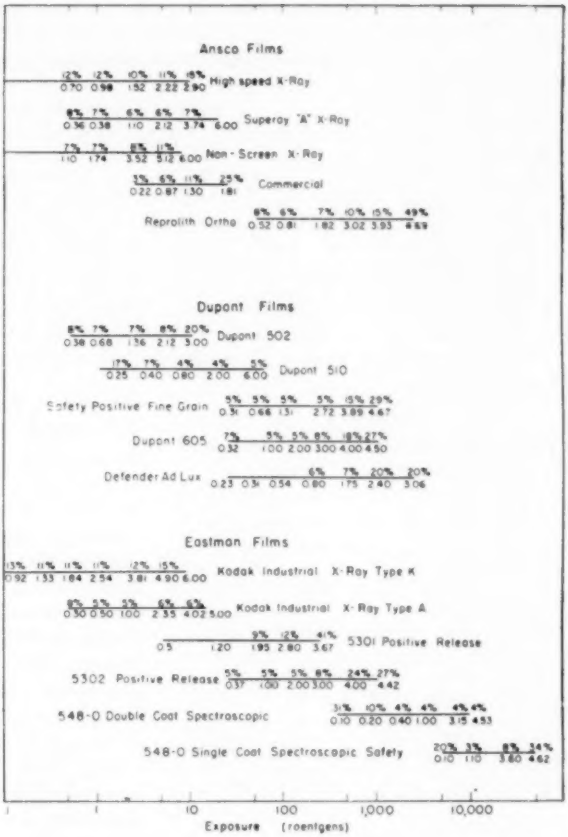

FIG. 7. Calibration of 16 emulsions with X-rays generated at 1.4-Mv exciting potential. Numbers below the lines are the photographic densities at the particular exposures; numbers above the lines are the per cent accuracies of the emulsions at the particular exposures

1,000 r with adequate accuracy. Three emulsions cover the range 30–500 r: Ansco Reprolith Orthochromatic, Dupont Safety Positive, and Dupont 605.

The Ansco film was excluded because experiments had shown that it fogs in the Wratten safe light 6B which is safe for use with the other films. The Dupont 605 film was selected. For the coverage of the range 1–50 r, Dupont 510 was chosen, even though it overlaps slightly with the Dupont 605 film. This provides a useful check on the performance of these two films. Also as a performance check, Eastman 5302 Positive film was added to the selection.

The four selected films, in standard dental packets, constitute the essential part of the film dosimeter.

Selection of absorbers. Table 1 shows the photographic response coefficients calculated from the calibration data as r_2/r_1, where r_1 is the dosage to which an emulsion is exposed at a specified low voltage, and r_2 is the dosage yielding the same density in the million-volt region as r_1 produces at the low voltage. The densities corresponding to both dosages are in the linear range of the characteristic curves, except in the case of the Eastman 548-0 film, where the dosages are in the low-density

TABLE 2
Theoretically Determined Absorber Thicknesses

Exciting potential (kv)	*Absorber thicknesses (cm)*							
	Dupont 510		*Dupont 605*		*Eastman cine positive 5302*		*Eastman spectroscopic 548-O (double coat)*	
	Lead	*Tin*	*Lead*	*Tin*	*Lead*	*Tin*	*Lead*	*Tin*
100	0.093	0.135	0.084	0.125	>0.108	>0.146	0.105	0.144
150	0.049	0.222	0.046	0.210	0.33	0.169	0.054	0.245
200	0.069	0.332	0.046	0.235	0.54	0.282	0.075	0.392
250	0.071	0.350	0.049	0.266	0.22	0.100	0.071	0.350

TABLE 3
Inaccuracies in Dosage Interpretation 35- to 600-kev Range

Energy (kev)	*Per cent inaccuracy**			
	Dupont 510	*Dupont 605*	*Eastman 5302*	*Eastman 5480 (double coat)*
35	−93	−93	...	...
80	−33	−54	−69	−60
115	+6	−19	−47	−20
150	+24	+7	−25	−15
200	+10	+2	−23	−4
350	+7	0	−11	−2
600	0	0	0	0

* Due to energy dependence.

range in which this film is actually used.

The thicknesses of lead and tin absorbers suitable for removing the energy dependence of the four selected emulsions are found by matching the response coefficients of Table 1 and the dosage-reduction ratios of Fig. 6. Table 2 shows the results. The required absorber thicknesses vary considerably with exciting potential.

It was then attempted to find a filter for each of the emulsions which would fit all four exciting potentials. For better visualization, the pertinent reduction-ratio curves are plotted along with the film-response curves in Fig. 8. The figures show that while the course of the lead-reduction curves parallels the response curves in the range from 200- to 250-kv exciting potential, the lead reduction is insufficient at lower voltages. On the other hand, a tin absorber alone is seen to be satisfactory only for the Eastman Positive film 5302. For the three other emulsions, the tin absorber, which looks satisfactory above 200 kv, is too thick at lower exciting potentials. It was therefore expected that for these three films a combination of tin and lead would be more suitable.

The effect of various combinations was calculated. Figure 9 shows the performance expected of the best combination for each film type. These combinations seem to suppress the response at 100 kv more than is desired, but seem satisfactory otherwise. However, since all four emulsions were to be combined in one dosimeter, a further compromise had to be made. An absorber combination of 1.07 mm of tin and 0.3 mm of lead was finally selected.

Description and test of dosimeter. Figure 10 illustrates the assembly of the film dosimeter. The selected absorbers are shaped over a Bakelite film container. The tin is in contact with both the Bakelite and the lead covering the tin so that lead fluorescent radiation is stopped in the tin absorber. A lead strip, approximately 0.78 mm thick, is

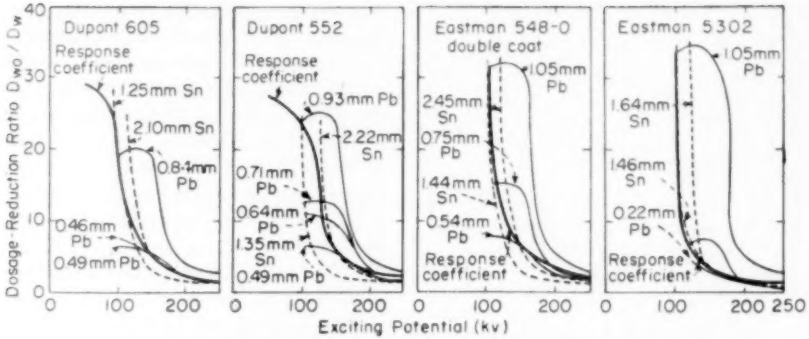

FIG. 8. Matching of dosage reductions and response coefficients

then wrapped around the periphery of the badge to protect the films from tangential radiation and at the same time cover the badge seam.

Table 3 shows the results of a calibration of this badge with X-radiation whose effective energies were between 35 and 600 kev, as shown by absorption curves. As was expected, the response of all the films is suppressed too much at voltages below 115 kev, while the response of Eastman 5302 is excessively suppressed throughout the entire interval. The other three films, however, allow a dosage interpretation accurate within 25% over the energy range 115–600 kev. The fact that the Eastman 5302 film indicates a dosage about 25% too low, between 150 and 200 kev, while the Dupont 605 film, which covers the same dosage interval, indicates the dosage within 7%, makes it possible to draw conclusions regarding the radiation components in this spectral range.

The Bakelite container was chosen for its mechanical ruggedness and heat-resistive properties as well as to produce electronic equilibrium. The container walls were made 8.25 mm thick, which is just sufficient to stop external secondary electrons produced by X-rays from a 10-Mev betatron; electrons originating within the container itself reach the

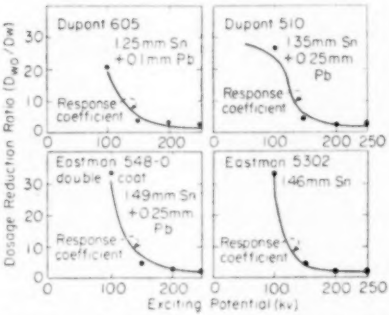

FIG. 9. Performance expected of the best absorber combination for four emulsions. ▲ The points are the dosage reductions

FIG. 10. Dosimeter parts. Left: back view of Bakelite mold. Middle: half of film container, coated with lead and tin, showing indentation for film packet. Right: Finished badge before lead strip is put over seams

film emulsion. Any additional absorber thickness will, therefore, only attenuate the primary beam, but will not increase the number of secondary electrons reaching the film surface. In this way, the point-to-point variation of

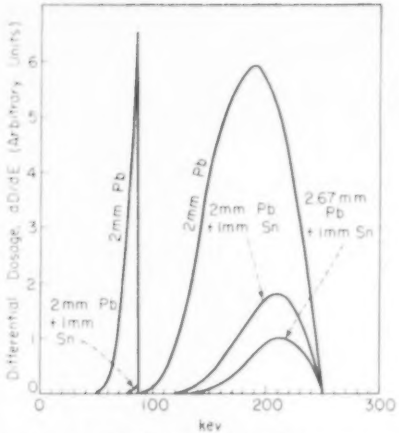

FIG. 11. Modification of 250-kev radiation spectrum by filters

the total energy absorbed in the layer is made to parallel roughly the absorption of X- and gamma rays. One usually refers to this situation as electronic equilibrium. The response of emulsions exposed under conditions of electronic equilibrium is independent of electrons scattered from nearby structures.

Calibration

The photographic dosimeter was calibrated with the X-radiation from a 10-Mev betatron and from a 1.4-Mv constant-potential X-ray unit. The dosimeter was also checked at six points of lower radiation energies (see Table 3). The calibration was made against a Victoreen roentgen meter with equilibrium wall thickness, which in turn was calibrated against a standard free-air chamber. Since Bakelite was the equilibrium material around the photographic emulsions, Lucite, whose effective atomic number is close to that of Bakelite, was chosen as equilibrium material around the Victoreen thimble.

In the energy range from 30 to 200 kev, where the film sensitivity varies by as much as a factor of ten with the spectrum of the exposing radiation, it is necessary to select the beam spectrum carefully and to specify it adequately.

The absorber combinations and absorber thicknesses used to obtain the specified radiation spectra from a constant-potential X-ray machine were determined theoretically by considerations based again on the modification of a triangular X-ray spectrum by absorbers.

While it is true that added filtration in the X-ray beam makes the X-ray spectrum more nearly monochromatic, it also reduces the dosage in the required energy range. The reduction of the dosage rate means increased exposure time for the calibration. A compromise is therefore required. In the present work, a dosage of 0.025 r/min/ma at one meter from the target is considered acceptable.

The method of selecting filter combinations for the various exciting potentials is best illustrated by an example. Figure 11 gives the differential dosages, dD/dE, at 250-kv exciting potential behind a 2-mm lead filter; its modification when 1 mm of tin is added to the lead; and, finally, the differential dosages behind a filter consisting of 2.67 mm of lead and 1 mm tin. The spectrum behind the lead filter shows clearly that the effect of lead filtration is negligible below the absorption edge. A sufficiently thick tin filter must be added to reduce the portion of the spectrum below the lead absorption edge, and in this way to narrow the transmitted spectral band.

An experimental test of this lead-tin combination filter revealed that the half-value layer of the radiation which it passes is 3.3 mm of tin and the beam intensity is 0.049 r/min/ma at one meter, about twice the desired intensity.

Figure 12 shows the half-value layers calculated for a number of points of an experimental tin-absorption curve plotted against tin thickness at 250-kv exciting potential. The half-value layer

of the originally selected filter (point A on the curve) is seen to lie in a region where half-value layer still varies appreciably with filter thickness. This is an expression of the fact that the radiation passing through the filter is still highly heterochromatic.

The addition of another half-value layer of lead to the original filter combination produces a more adequate result (point B in Fig. 12). The new filter passes a radiation intensity of 0.025 r/min/ma at one meter, which is the desired output. Similar reasoning led to the choice of filters for all other desired calibration potentials.

Figure 13 shows the theoretical spectral distributions passed by the calculated filters. In the case of the spectrum from the 100-kv exciting potential, the lead filter used cuts out all the X-rays above 87 kev.

To specify the beam quality in each case, a "spread" is defined as

$$W = (E_{\frac{1}{2},2} - E_{\frac{1}{2},1})E_{exc}/E_p$$

where E_{exc} is the exciting potential, E_p is the energy of the intensity peak, and $E_{\frac{1}{2},2} - E_{\frac{1}{2},1}$ is the energy band width at half of the peak intensity.

Table 4 lists the characteristics of the selected filtrations. It shows their theoretical spread, W, and the experimentally determined radiation intensity which passes through them. The experimentally determined half-value layers and the effective potentials of the resulting X-ray beams, as well as their theoretical intensity peaks, are included for comparison.

If lower intensities are acceptable, the spreads may be decreased by adding more filter material. In the case of combination filters, only the thickness of the high atomic number element has to be increased.

The exposed films were developed for five minutes in fresh Eastman X-ray developer at a temperature of 20 ± 0.1° C and fixed, washed, and

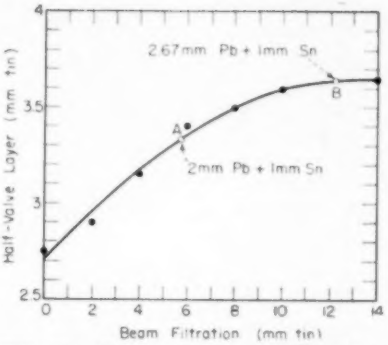

FIG. 12. Half-value layers of X-rays as a function of filtration for a 250-kv exciting potential

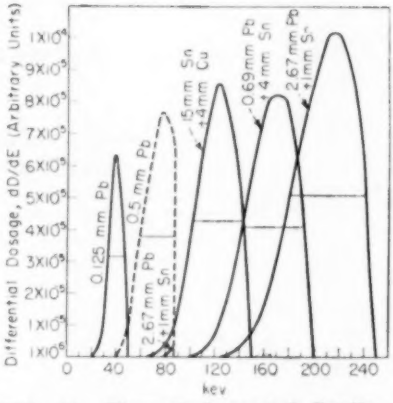

FIG. 13. Theoretical spectral distributions of the calibrating radiations. To read ordinates of dashed curve, multiply scale by 2

dried under standard conditions. A set of control exposures was developed along with each batch of calibration films. The photographic transmission densities were then read on a photoelectric densitometer with a range up to transmission densities 6 on the Hurter and Driffield scale. The high density range extends the useful exposure range of each film emulsion.

The results of the calibration of the dosimeter described here are shown in Figs. 14 and 15. The data are presented

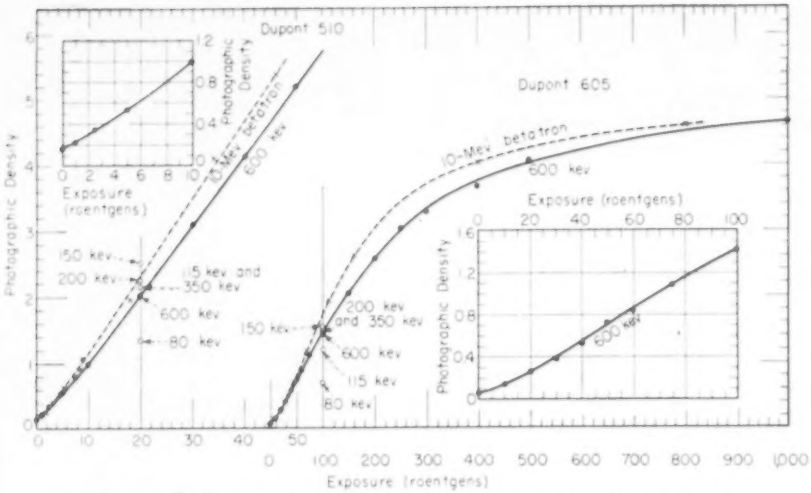

FIG. 14. Calibration of the film badge in the range 1–1,000 roentgens

TABLE 4
Characteristics of the Selected Filtrations

Filter	*Exciting potential (kv)*	*Spread (kev)*	*Half-value layer (mm tin)*	*Intensity peak, theoretical (kev)*	*Effective potential, experimental (kev)*
2.67 mm Pb +1 mm Sn	250	42.1	3.64	216.5	200
0.69 mm Pb +4 mm Sn	200	64.7	2.19	170	154
1.53 mm Pb +4 mm Sn	150	50.0	1.01	123	117
0.52 mm Pb	100	35.5	0.33	77.5	79
0.125 mm Pb	50	17.5	0.08	35.5	—

in the form of plots of photographic density vs exposure in roentgens for an effective radiation energy of 600 kev and for the radiation from a 10-Mev betatron.* Five low-energy points are included in the graph for comparison.

Table 5 shows the accuracies in the dosage interpretation to be expected in the range from an effective energy of 115 kev to the effective energy of a 10-Mev betatron. Some data for even lower energies are shown as well. The accuracy is ±12% in the dosage range from 1 to 50 r and from 1,000 to 10,000 r, while in the range from 50 to 1,000 r it is about ±20%. No further knowledge of radiation quality is necessary to stay within these limits.

* While the roentgen is actually not defined in the region of betatron energies, it is nevertheless felt that the reading of a Victoreen thimble with a low atomic number equilibrium layer is adequate for the present purpose.

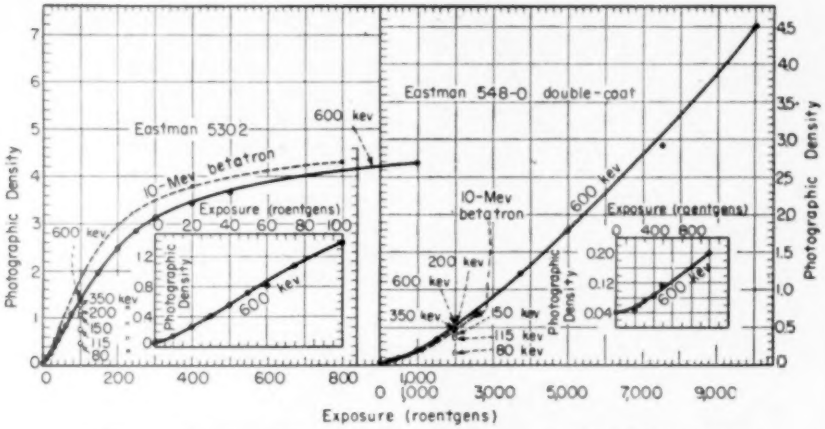

FIG. 15. Calibration of the film badge in the range 1,000–10,000 roentgens

TABLE 5

Inaccuracies in Dosage Interpretation 115-kev to 10-Mev Range

Film type	*Per cent inaccuracy**			
	Effective energies 115–350 kev	*Effective energy 600 kev*	*Betatron 10 Mev*	*Over-all*
Dupont 510	+6 to +24	0	+14	24
Dupont 605	−19 to +2	0	+23	42
Eastman 5302	−47 to −11	0	+36	83
Eastman 548-0 (double coat)	−20 to −2	0	−4	20

* Due to energy dependence.

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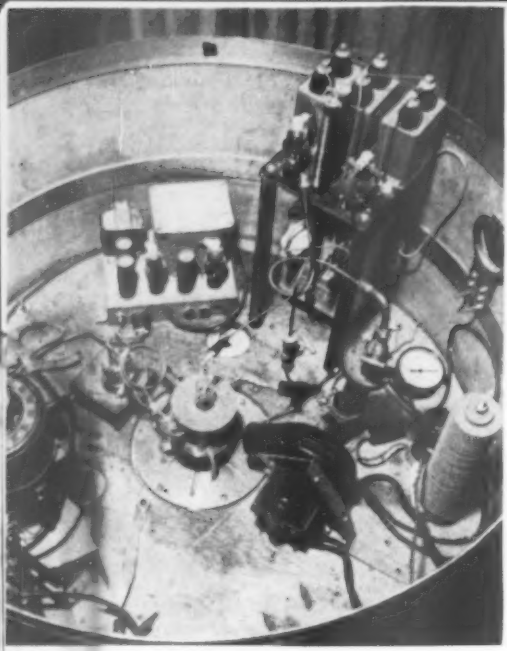
BIBLIOGRAPHY

1. R. H. Morgan, *Radiology* **42,** 471 (1944)
2. National Bureau of Standards, unpublished data
3. R. Berthold, R. Glocker, *Z. Physik* **31,** 259 (1925)
4. G. E. Bell, *Brit. J. Radiology* **9,** 578 (1936)
5. E. Tochilin, R. H. Davis, J. Clifford, ADP-78 (1949)
6. R. Baker, L. B. Silverman, NUCLEONICS **7,** No. 1, 26 (1950)
7. L. A. Pardue, N. Goldstein, E. O. Wollan, MDDC-1065 (1948)
8. L. J. Deal, F. H. Day, *Am. J. Roentgenol. Radium Therapy* **59,** 731 (1948)
9. H. A. Kramers, *Phil. Mag.* **46,** 836 (1923)
10. H. Kulenkampff, *Ann. Physik.* **69,** 548 (1923)



R-f ion source in place on Cockroft-Walton accelerator. Ion source is in center; across from blower pointed at it is r-f oscillator. Above oscillator is its power supply, and then, clockwise, are the 5-kv probe supply, gas line and pressure gage, and selenium rectifier stack of magnet-coil power supply

Design and Operation of

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UNTIL RECENTLY, nearly all ion sources used with high-voltage accelerators have been of the filament type. But in the past few years much interest has been shown in the electrodeless discharge ion source. This interest results from the fact that the radio-frequency ion source compares favorably with other types in power consumption and compactness and excells in meeting other requirements.

Another reason for interest in r-f ion sources is the change in accelerator design in recent years. For example, long source life has become increasingly important on Van de Graaff generators enclosed in pressure tanks, since as much as a day is required to perform even minor adjustments inside.

A number of r-f ion sources have been described in various journals (*1–4*). A summary of the results obtained has been given by Ward (*5*). The source to be described in this article is an adaptation of the design of Thoneman (*3*), with certain modifications which simplify construction and assure uniformity of results.

Two separate problems arise in the design of an r-f ion source: production of an intense atomic hydrogen discharge, and extraction of large proton currents. These problems and their solution will be considered before the construction and operation of the source is discussed.

The Hydrogen Discharge

The experiments of Wood (*6*) many years ago proved that if a hydrogen discharge is set up in a vessel consisting of a very long tube of clean Pyrex glass

For use with an accelerator, an ion source should exhibit:

1. Stability and long life.
2. Large beam current.
3. Low gas consumption.
4. A high proton percentage.
5. Simplicity of construction.
6. Low power consumption.
7. Compactness.

The source described here delivers 1.25 ma of positive ions, over 90% of which are protons, and has a usable life of more than 500 hours.

a Radio-Frequency Ion Source for Particle Accelerators

with high-voltage electrodes at the ends, then the center section of the tube (most removed from the metal electrodes) exhibits an almost pure Balmer spectrum. The Balmer spectrum denotes the existence of atomic hydrogen, and if ions could be extracted from such a discharge without recombining the atomic hydrogen to molecular hydrogen, the resulting ion beam should have a very high percentage of protons. Wood found that the ends of the discharge tube near the metal electrodes exhibited the molecular spectrum of hydrogen, indicating that metals are very good catalysts for recombination.

Experiments were conducted by Thomson (7) on discharge vessels containing no metals, the discharge being supported by an induction coil wound on the Pyrex vessel. In these experiments the most intense part of the discharge was found to exhibit an almost pure Balmer spectrum, once again illustrating that Pyrex is a very poor catalyst for recombination.

At the pressures commonly used (50 μ or less) the mean free path of the ions is much greater than the vessel dimensions so that volume recombination effects are negligible compared to surface recombination effects. Since Thomson's experiments, measurements of surface recombination coefficients for various materials have been performed which show that Pyrex glass is the poorest known catalyst for hydrogen recombination. For example, Smith (8) measured the recombination coefficient for various materials and obtained the following values: Pyrex, 2×10^{-5}; quartz, 7×10^{-4}; Al_2O_3, 0.33; and Pt, 1.0. Recombination coefficients for all metals which have been studied have been found to be near unity.

The natural conclusion is that a discharge supported by externally applied r-f excitation, in a vessel containing as little metal area as possible and consisting of carefully cleaned Pyrex, should produce ions with a very high percentage of protons.

Radio frequencies ranging from 20 to 450 megacycles/sec have been used to excite atomic hydrogen discharges. At the higher frequencies a magnetic field

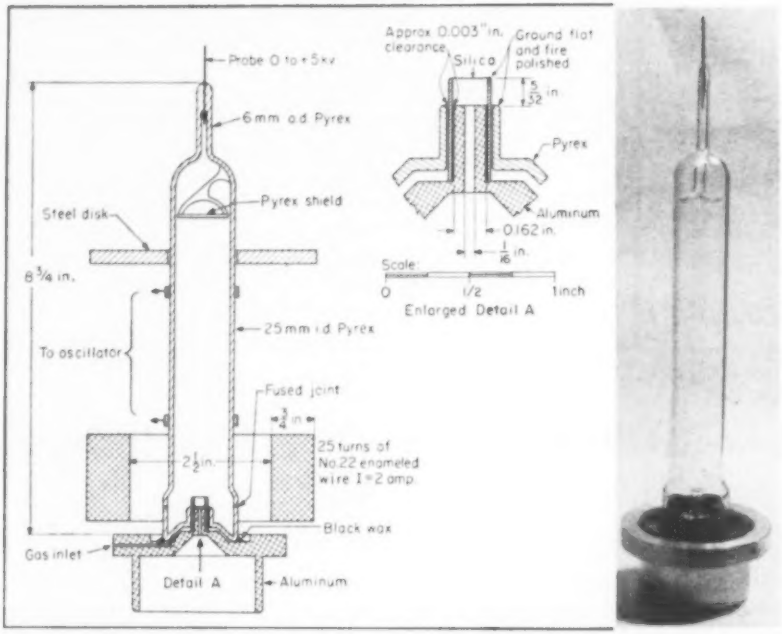


FIG. 1. Cross section of ion source and completed assembly of glass vessel and aluminum base. Details of extraction geometry are shown in enlarged view

will reduce the r-f power requirements by restricting the electron paths, thus increasing the ionization probability per electron released. This reduction in r-f power minimizes dielectric heating problems, although the power saving is usually lost to the magnet coil.

In general, lower frequencies require the use of a larger discharge vessel, as shown by the experiments of Gill and Von Engel (*9*). The experiments of Koch and Neuert (*10*) indicate that these discharges will have an r-f impedance which is capacitive, resistive, or inductive depending on magnetic field, frequency, and vessel dimensions, so that some experimentation with oscillator loading is required. Because of the impedance matching problems encountered, the use of a self-excited oscillator seems desirable. With 20-megacycle excitation, good matching can be obtained by mounting the discharge vessel inside the oscillator tank coil. At 100 megacycles/sec we have found that capacitive coupling of the oscillator tank coil to two external electrodes on the discharge vessel is preferable.

Extraction

Ward (*5*) has pointed out that probe extraction seems to give greater gas economy without introducing any appreciable energy spread to the ion beam. A very good solution of the extraction problem was developed by Thoneman.

Proper construction of the extraction system, the most critical part of the ion source, may make the difference between a 30 μa beam and 1,200 μa beam. The extraction system consists of a small tungsten anode hidden from the discharge by a short capillary, and a cathode consisting of a cylindrical aluminum tip protruding into the vessel at

the other end of the discharge. A small canal in the aluminum tip carries the ions into the accelerator tube.

The essential feature of the cathode design is the use of an insulating sleeve mounted over the canal tip to serve the dual purpose of hiding the metallic cathode from the discharge and of functioning as a virtual anode when the extraction voltage is applied. With proper shaping of the canal tip and the insulating sleeve, and with careful orientation of the two parts, a lens is formed over the canal which focuses a large number of ions with paths straight enough to miss the walls of the canal. The function of the insulating sleeve is as follows:

As the extraction voltage is increased, a cathode dark space develops between the canal tip and the luminous body of the discharge. Finally, a roughly spherical plasma boundary is formed over the mouth of the insulating sleeve. This boundary can be considered to be the proton-emitting surface. As the ions are accelerated toward the cathode, they first fall through a roughly spherical field and are directed toward the axis, but the equipotentials gradually flatten upon approaching the canal-tip and thus the trajectories are straightened upon entering the canal.

These effects are easily observed visually. As the extraction voltage is increased a circle of fluorescence appears on the flat face of the canal-tip. Further increase of voltage causes this circle to shrink until it finally disappears into the canal; at this voltage the output current is a maximum.

In our experiments on these sources we have found that reducing the inside diameter of the sleeve in Thoneman's design from $\frac{1}{4}$ to $\frac{3}{16}$ in. improves the focusing considerably; however, use of this smaller diameter increases the electric field-strengths in the Pyrex sleeve and it is destroyed by a spark. Since Pyrex is a much poorer insulator than fused silica, especially when warm, we decided to modify Thoneman's original design to the extent of using a silica sleeve, covered as much as possible with Pyrex. The modification also makes fabrication to close tolerances much simpler. The sleeve is a short length of fused silica tubing, carefully ground flat on the end and lightly fire-polished to cover traces of grinding compound.

The use of a magnetic field has been found to have the additional advantage of increasing the output current by limiting space-charge-spreading in the canal. The aluminum tip at the top of the canal must be flat and perpendicular to the axis. Twenty-degree bevels have been tried (both inward and outward) with a loss in output of approximately 80%. The use of a spherical tip reduces the output from 1,200 μa to approximately 30 μa.

A cross section of the ion source now in use on the Cockroft-Walton accelerator at Oak Ridge National Laboratory, and an enlarged view of the extraction geometry finally adopted for this source are shown in Fig. 1 with a picture of the Pyrex vessel and aluminum base. The hydrogen is fed in through the base of the source to avoid high-voltage isolation problems. A copper feed line is connected between the source and a hydrogen tank containing a palladium leak. It is very important that the feed system be completely free of leaks and contaminating vapors since the quality of the discharge is very sensitive to extraneous gases.

Secondary electrons from the canal tip tend to be focused at the top of the vessel by the magnetic field. The steel disk defocuses these electrons and permits them to be caught by the Pyrex shield without damage.

Construction

The fused-silica sleeve must fit snugly into the outer Pyrex sheath to prevent sparking from the discharge to the

aluminum base, but a few thousandths of an inch clearance must be left for thermal expansion. The inside diameter of the silica sleeve should be 0.003 in. greater than the outside diameter of the aluminum canal tip to allow for thermal expansion and still maintain accurate alignment. The height of the fused silica sleeve above the canal tip is not quite as critical but should be held to $\pm\frac{1}{64}$ in. Small changes of not more than $\frac{1}{64}$ in. in the diameter of the canal tip seem allowable when fitting the silica sleeve to the tip.

The Pyrex base of the vessel is a separately molded part. The technique for making this part was developed by C. Asmanes of the glass shop at the K-25 plant in Oak Ridge. His procedure is as follows:

A stainless-steel mold, cut to the shape of the bottom of the vessel and roughly resembling the aluminum base, with a tip diameter equal to the outside diameter of the silica tubing, is mounted in the rotating right-hand spindle of a glass-lathe. In the left-hand spindle is mounted a length of Pyrex tubing (inside diameter, 35 mm) with a connection through the spindle to a compressed-air valve. The tubing is sealed off on the end, flattened, and the glass worked to uniform thickness. With proper preheating of the glass and the mold, the mold is advanced rapidly into the end of the tubing. Compressed air is used to lay the glass down on the mold.

Upon cooling, the mold shrinks free and can be withdrawn. The molded base is then sawed off at the length required to give the right Pyrex inner sleeve length. The Pyrex sleeve is lightly fire-polished to cover any traces of grinding compound.

The upper assembly is made of a section of Pyrex with an inside diameter of 25 mm, flared at the bottom and welded to the molded base. These Pyrex vessels will soon be available from Radiation Counter Laboratories, Inc., Chicago 8, Illinois.

After fabrication, the vessel must be carefully cleaned before being attached to the base. It is very important that great care be used in treating the inside surfaces of the vessel. An example will serve to illustrate this point. Ion sources prepared with no special treatment of the glass walls usually give H_1^+/H_2^+ ratios of 2–3. If the glass is first treated with boiling nitric acid, followed by rinsing with distilled water, H_1^+/H_2^+ ratios of 7–8 are observed. Treating the glass with a dilute solution of HF (not enough for severe etching) followed by distilled-water rinsing gives H_1^+/H_2^+ ratios of 12–15.

The vessel may be fastened to the aluminum base with either Vinyl-Seal or black wax. In some cases it may help to grind the bottom of the Pyrex vessel lightly to make good contact with the aluminum base. The base may be modified below the canal to suit the lens requirements of the accelerator.

Circuits for the oscillator and power supply are given in Fig. 2. The r-f power delivered to the discharge is approximately 60 watts at 100 megacycles.

The external r-f electrodes are VG-1A ionization-gage plate-clips connected to the oscillator tank coil by copper-braid clip-leads. The best oscillator loading is obtained with the leads clipped to the tank-coil approximately $\frac{2}{3}$ of the distance from the center-tap to the plates.

Operation and Performance

When one of these sources is started for the first time, the extraction voltage should be left off while the discharge changes from white to red as extraneous gases are pumped out of the source. The hydrogen pressure should be adjusted to approximately 15 μ. Cleanup should take less than 15 minutes. After cleanup the magnetic field pro-

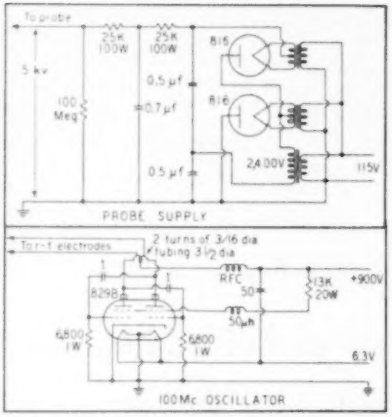


FIG. 2. Oscillator and probe power supply. Circuit of power supply for oscillator is not shown

duces a pronounced reddening and an increase in the intensity of the discharge. Aluminum has been used as a cathode to minimize the effects of sputtering. After several hundred hours of operation the walls of the vessel will be discolored by sputtered aluminum from the tip. This metal may be removed with HF.

The characteristics of this ion source under typical operating conditions with hydrogen, and when set at maximum current, are as follows:

Total output current	1.25 ma
H_1^+	1.15 ma
H_2^+	0.08 ma
H_3^+	0.02 ma
Total power consumption	500 watts
Gas consumption	6 cm^{13}/hr (atmospheric pressure)

This source has also been used with He, A and Xe, giving total output currents of 0.50, 0.10, and 0.02 ma respectively. In each case the ions were almost all singly charged.

We have investigated the dependence of output current on canal diameter and find that the current varies as the square of the canal diameter. If a reduction in beam current can be tolerated, considerable improvement in gas economy may be achieved. For example, a source having a 0.040-in. diameter canal has been found to give a total current of 0.47 ma with a gas consumption of only 2 cm^3/hr.

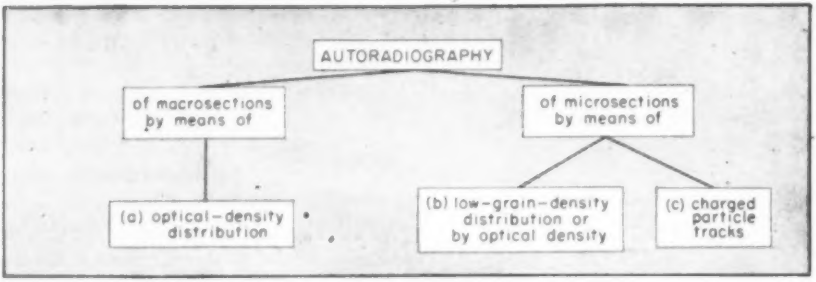
Conclusion

The development of high-current ion sources has put a greater emphasis on the design of the accelerator tube and its focusing elements. To avoid serious loading difficulties on accelerator electrodes, a smaller percentage of the beam can be allowed to escape the focusing system. When serious space-charge-spreading occurs, some attention must be given to the over-all magnification of the lens system used. It is advisable to keep the control elements of the lens system well hidden from the direct beam and from counter-flowing electrons in the accelerator tube to avoid overloading the lens power-supplies. In the 0.3-Mev Cockroft-Walton accelerator at Oak Ridge National Laboratory, the beam is brought to a focus after mass analysis at a distance of 2 meters from the base of the accelerator with a spot diameter of 3 mm.

The r-f ion source described has been used interchangeably with protons, He^{3+} and He^{4+} during the past eight months; it has been found to be quite stable, requiring no attention for periods as long as 30 hours.

BIBLIOGRAPHY

1. J. G. Rutherglen, J. F. I. Cole, *Nature* **160,** 545 (1947)
2. A. J. Bayly, A. G. Ward, *Can. J. Research* **A26,** 69 (1948)
3. P. Thoneman, J. Moffatt, O. Roaf, J. Sanders, *Proc. Phys. Soc. (London)* **61,** 483 (1948)
4. R. N. Hall, *Rev. Sci. Instr.* **19,** 905 (1948)
5. A. G. Ward, *Helv. Phys. Acta* **23,** 27 (1950)
6. R. W. Wood, *Proc. Roy. Soc. (London)* **A97,** 455 (1920)
7. J. J. and G. P. Thompson, "Conduction of Electricity through Gases" vol. II (Cambridge University Press, London, 1928)
8. W. V. Smith, *J. Chem. Phys.* **11,** 110 (1943)
9. E. W. B. Gill, A. von Engel, *Proc. Roy. Soc. (London)* **A192,** 446 (1948)
10. B. Koch, H. Neuert, *Z. Naturforsch.* **4a,** 456 (1949)


AUTORADIOGRAPHY
of macrosections by means of
of microsections by means of
(a) optical-density distribution
(b) low-grain-density distribution or by optical density
(c) charged particle tracks

Photographic Fundamentals of Autoradiography

In choosing a suitable photographic medium, the sensitivity and resolution attainable must be considered along with the type and energy of radiation to be recorded. New emulsions and specialized photographic material are resulting in a variety of new, promising autoradiographic techniques

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RECENT PROGRESS in photographic emulsions for recording particle tracks has laid the foundation for new techniques in autoradiography. These techniques make it possible to obtain high resolution records of the distribution of radioactive tracer materials in microscopic specimens.

Many different methods are now applied to record the distribution of radioactive material, particularly in regard to microscopic specimens. One of the guiding factors influencing the autoradiographic technique is the choice of a suitable photographic material, and it is the chief purpose of this review to familiarize the reader with the characteristics of various photographic emulsions for various uses.

In its present stage, the various techniques used in autoradiography may be divided as shown in the family-tree diagram above. Although the three methods indicated frequently overlap in practice, it may be said that (*a*) is the oldest and best established method, (*b*) is now in the focal point of interest, and (*c*) is still in its infancy.

The tracers used in autoradiography are usually artificial radioisotopes emitting electrons, positrons, or alpha particles, and, in many cases, gamma rays. The majority of isotopes useful as biological tracers are beta-ray emitters.

The three techniques will be dealt with in the order given above.

Autoradiography of Macrosections

Autoradiography of macrosections (*1–8*) entails recording the distribution of radioactive materials in gross sections such as those of plants, minerals, skins of fishes, or sheets of wood. Enlargements of a few diameters may be re-

TABLE 1
Initial Activity and Number of Electrons Per Square Centimeter Required to Obtain a Density of 0.6 Within Exposure of 15 Days (Eastman No-screen Film)

Isotope	*Maximum energy of beta particle (Mev)*	*Activity ($\mu c/cm^2$)*	*Electrons/cm²*
C^{14}	0.154	3.6×10^{-4}	0.38×10^7
Ca^{45}	0.26	4.6×10^{-4}	2.0×10^7
I^{131}	0.6	9.8×10^{-4}	2.65×10^7
P^{32}	1.71	2.1×10^{-3}	7.2×10^7

quired, but nevertheless the purpose is to record gross or macrosections of a specimen.

The techniques involved are usually straightforward and do not require such familiarity with the characteristic properties of photographic emulsions as is necessary when dealing with microsections. The photographic material used is X-ray film of high or medium sensitivity. The choice depends on the resolution required. X-ray films of medium sensitivity, which are useful, for example, in industrial radiography, are finer grained than the high-speed X-ray films.

The basis of the technique is the placing of a specimen (such as a plant leaf containing a radioactive material) in contact with the suitable photographic material. After exposure and processing, the photographic layer reveals the location of the radioactive material within the specimen. The image obtained is called an autoradiograph.

The main technical problem in macroautoradiography is that of achieving intimate contact between specimen and film. Although sufficient contact may be achieved in many cases by pressure cassettes, such as ordinary printing frames, the most successful device is probably a vacuum cassette (*9*). Vacuum rubber cassettes are used in photomechanical processes and also in industrial radiography. For small specimens, they may be made from a bicycle or car tire.

Photographic response due to pressure and chemical effects may easily be produced from wet leaves or plants, and an autoradiograph may be simulated. Hence, the taking of a control photograph, which is explained later, is an absolute necessity. Thin layers of gelatin or celluloid may be interposed between specimen and film to avoid artifacts, but the interlayer will also impair the resolution obtainable.

In most cases, optical densities* are required. The highest sensitivity to electrons is obtained with double-coated X-ray films of the fast type. For slow electrons, only one coated side of such films is used. A comparison is given in Table 1 of the relative activities and number of electrons required to obtain a given density for various electron emitters.

These data of the activities in microcuries have been taken from MacDonald *et al.* (*5*) and the number of electrons (n_e) required per cm² have been computed from these figures by the author, using the relationship:

$$n_e = \frac{(\mu c)_0 \, 3.7 \times 10^4 \, (1 - e^{-\lambda t})}{\lambda}$$

* The optical density is defined as $D = \log I_0/I_1$, where I_0 is the incident and I_1 the transmitted light intensity.

where $(\mu c)_0$ = microcuries, λ = decay constant (sec^{-1}), and t = exposure time in sec.

It is seen from this table that, with slow electrons, such as those from C^{14}, as compared with those from P^{32}, only about $\frac{1}{20}$ the number of incident electrons is required to obtain equal density. Results very similar to those reported by MacDonald were obtained by the author using P^{32} and I^{131} on X-ray films.

The extremely high sensitivity of the photographic method in detecting minute quantities of radioactive material can be seen from the fact that only 1.5×10^{-16} gm of P^{32} per mm^2 are required to obtain, within one day's exposure, an optical density of $D = 0.5$.

Autoradiography of Microsections

When dealing with the autoradiography of microsections for recording optical or low-grain density or particle tracks, a certain familiarity with the response and the characteristics of special photographic emulsions to electrons and also to other charged particles is necessary.

Photographic response to charged particles (*10–17*). Nuclear track emulsions have been chosen for autoradiographic work of microsections because they combine a fine grain with high intrinsic sensitivity and close packing of grains. This feature makes them particularly suitable for high resolution work in connection with charged particles. The close packing requires high concentration of silver halide in gelatin. The grain size of the emulsion is of the order of 0.2–0.5 microns, depending on the sensitivity of the grains.

Whether the final aim of the autoradiograph is to inspect a low-grain-density distribution, a particle track, or an optical density, the response of the nuclear track emulsion will be based on the following considerations.

The photographic layer consists of a large number of tiny crystals of silver bromide embedded in gelatin. The number of grains per cm^2 of emulsion is of the order of 10^9–10^{12} depending on grain size and thickness of coating. If a charged particle, such as an electron or alpha particle, travels through a nuclear track emulsion, it loses energy as a result of interactions of various types with atoms lying near its line of motion. One of these interactions is the collision with the orbital electrons of the atoms through which it passes. These electrons may be ejected from the atoms (ionization) or the atoms may be left in excited states.

Thus a silver bromide grain may be rendered developable because of the ionization produced by the passage through it of a fast charged particle. Hence the path of a charged particle in the emulsion might be recognized as a track made up by a row of developed silver bromide grains when viewed under the microscope.

The rate of energy loss per unit length

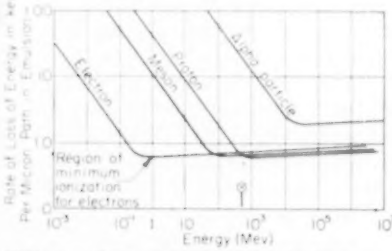


FIG. 1. Rate of energy loss (in kev) per micron as function of energy (in Mev) for electrons, mesons, protons, and alpha particles. Above the energy marked by X, all single charged particles are recorded as straight-line minimum ionization tracks

FIG. 2. Track (~300 μ length) of an electron produced by a 1.3-Mev Van de Graaff generator (Kodak NT4 emulsion)

of path, dE/dX, which is proportional to the number of ions produced per unit length of path (also called specific ionization), varies directly with the square of the charge of the incident particle, inversely as the speed of the incident particle, and directly with the number of electrons per cm^3 of the stopping material.

A formula which permits the computation of the rate of energy loss of electrons per unit length of path as a function of energy has been derived by Bethe. This formula has been generalized for heavy stopping material (silver and bromine of the emulsion) and adapted for composite stopping material. The computation has been carried out for electrons and other charged particles, such as mesons, protons and alpha particles and is shown in Fig. 1 for the composition of Kodak Nuclear Track emulsions.

In Fig. 1, the relationship is shown between the rate of energy loss in kev per micron of emulsion and the energy of the incident particles in terms of million electron volts (Mev). The energy dissipation per grain required by a charged particle to render the grain developable is a measure of its intrinsic sensitivity. As seen in Fig. 1, a charged particle loses more energy per unit length of path, the smaller its kinetic energy; hence silver bromide grains will, in general, be more sensitive to slow than to fast electrons.

The curves in Fig. 1 lead through a broad minimum (for electrons at an energy of about 1 Mev). In this region the particle is said to possess minimum ionizing power. If an emulsion is capable of recording recognizable tracks of electrons at minimum ionizing power, the emulsion is then said to be sensitive

FIG. 3. Track of a particle possessing minimum ionizing power

FIG. 4. Alpha-particle tracks

at minimum ionizing power and hence to charged particles of any energy.

The grain density, i.e., the number of developed grains per unit length along a track, depends on the rate of energy loss of the particle during its passage through the emulsion. As seen from the photomicrograph of an electron track in Fig. 2, the grain density increases towards the end of the trajectory when the particle slows down. Because of its small mass, an electron at low speed suffers many collisions and is, therefore, scattered in the emulsion. The higher the speed of the particle, the less it will be scattered. This is seen in Fig. 3 in a photomicrograph of the initial part of a track of an electron at minimum ionizing power.

Apart from electrons, only alpha particles appear to be of interest at present in autoradiography. As seen in Fig. 1 from an extrapolation of the alpha curve towards lower energies, the specific ionization (number of ions per unit length) of an alpha particle having the same energy as an electron of, say, 100 kv is several thousand times that of the electron because of the double charge of the alpha particle and because of the low speed associated with its relatively great mass. This explains the high grain density of an alpha particle track, as seen in Fig. 4.

Since the actual ranges of electrons and alpha particles in photographic emulsions are of interest to the worker

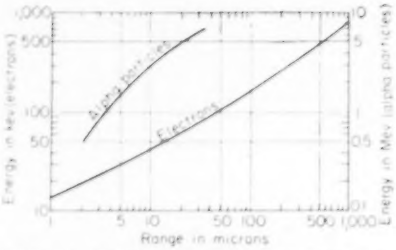


FIG. 5. Relationship between range and energy in kev for electrons and in Mev for alpha particles

in autoradiography, the relationship between range and energy for nuclear track emulsions is shown in Fig. 5. Experimental evidence for the accuracy of the computation has been shown for electrons up to 250 kv (*16–17*).

Nuclear track emulsions of different sensitivities are now available from Eastman Kodak Co. (U. S. A.), Ilford, Ltd. (England), and Kodak Ltd. (England). It is convenient to indicate their relative sensitivities in terms of the energy of charged particles capable of producing recognizable tracks. Of the various types of emulsions for nuclear research, there are three chief ranges of sensitivity which are of interest in autoradiography:

(**a**) low sensitivity (capable of recording alpha-particle tracks)
(**b**) medium sensitivity (capable of recording tracks of alpha particles and slow electrons up to energies of 80–100 kv)
(**c**) high sensitivity (capable of recording tracks of fast electrons at minimum ionizing power).

Only type (**b**) is of widespread use in autoradiography at present, since emulsions sensitive at minimum ionizing power suffer from the disadvantage that they rapidly accumulate tracks from cosmic rays and the radioactivity in the surrounding air. The problem of sensitivity in autoradiography will be discussed in more detail later.

Response to photons (*18–19*). The response of nuclear track plates to gamma rays is based on the absorption of photons and the simultaneous release of photo- and recoil electrons within the sensitive layer. Many of the artificial radioactive isotopes used for tracer experiments emit gamma rays of high energy, say, between 0.5–2 Mev. As the absorption of this radiation in the photographic layer is low compared with that of electrons, the response of the emulsion to gamma rays is relatively weak. For the same number of electrons and photons (of the energy mentioned above) incident on a nuclear track emulsion, the ratio of the number of grains rendered developable will be of the order of 100:1 respectively.

The emission of electrons by radioisotopes is often accompanied by the emission of gamma rays. Thus, from the preceding discussion, it can be concluded that the effect of the gamma rays will generally be negligible compared with that of the electrons.

With decreasing quantum energy of photons, the absorption coefficient for silver bromide increases and the electrons released by these photons are more likely to compete with the direct action of electrons impinging on the plate. If high sensitivity to gamma rays is required, emulsions other than nuclear track plates may be used. X-ray emulsions have the highest speed to gamma rays, but because of their relatively large grain size and thick double coatings, they cannot be recommended for autoradiographs of microsections. Nevertheless they are useful in the recording of macrostructures, as shown before. The gamma-ray sensitivity of double-coated X-ray emulsions is on the average about a hundred times greater than that of the thinly coated nuclear track emulsions, if referred to the same optical density.

The relative spectral sensitivity of X-ray films is shown in Fig. 6. The

graph illustrates the relative speed of X-ray films as a function of X-ray wavelength. This relation only holds for monochromatic or strongly filtered radiation. If the speed for any one wavelength is known, the corresponding multiplying factors for other wavelengths can be read off the curve. Since the spectral sensitivity to X-rays varies from one type of X-ray emulsion to the other, the curve can present only a rough guide to the reader.

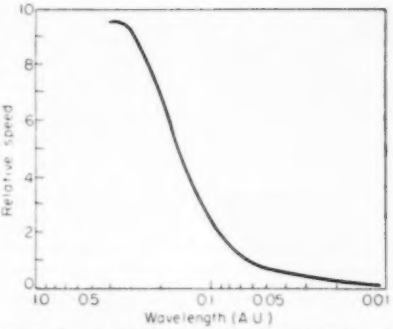


FIG. 6. Relative spectral sensitivity of X-ray emulsions

Techniques. In connection with the techniques used in autoradiography of microsections, such problems as the material, manipulation, photographic artifacts, controls, resolution, speed, exposure time, and quantitative evaluation must be considered. They are discussed below.

Material and manipulation (*1, 20–38*). In the original method of autoradiography used by Lacassagne and Lattes (1925), a specimen was simply placed in contact with the photographic plate or film. The contact was ensured by means of pressure. In the postwar period, when artificial radioactive isotopes became available and new potentialities in the detection of tracers by means of autoradiography appeared to be probable, first consideration was given to an improvement in resolution.

In 1946, Belanger and Leblond (*21*) described a method of improved photographic resolution. They detached photographic emulsions from plates, melted the emulsion, and painted a thin layer of it on the microsection. The combined system of emulsion plus section was left in a light-tight container for drying and exposure. The whole system was placed in the processing solutions and the specimen remained in permanent contact with the emulsion for microscopic inspection.

Evans in 1947 floated the section onto the photographic plate (*23*). After exposure, the paraffin wax of the section was dissolved so that the processing solutions could penetrate through the specimen, which was also kept in permanent contact with the emulsion.

The superposition of specimen and photographic emulsion is of great significance as it assists the location of the autoradiographic image with regard to the spatial distribution of the radioactive material within the specimen. Probably the most convenient method suggested so far involves the use of various types of stripping film or stripping plate as described by Pelc (*28*), by MacDonald, Cobb, and Solomon (*5*), and by Boyd and Williams (*31*).

One basic idea is that an emulsion layer is fastened to a very thin support which is in turn mounted on a temporary support. Both the emulsion and its thin support can be stripped from the temporary support and transferred to the specimen. The thin support is needed for protection of the emulsion layer which is only 5 μ thick and therefore easily damaged and virtually impossible to handle.

In the Eastman Kodak Co. (U. S. A.) stripping films, cellulose esters have been employed as the thin support.

The advantage of the thin support is that it provides an impermeable layer between the emulsion and the radioactive specimen, avoiding any artifacts

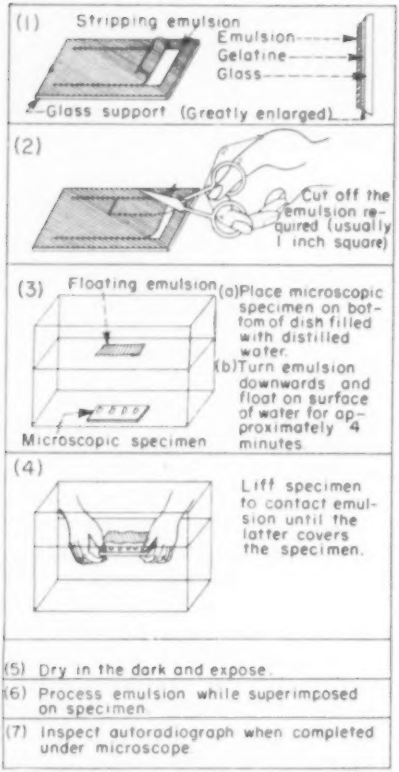

(1) Stripping emulsion
Emulsion
Gelatine
Glass
Glass support (Greatly enlarged)
(2)
Cut off the emulsion required (usually 1 inch square)
(3) Floating emulsion
(a) Place microscopic specimen on bottom of dish filled with distilled water.
(b) Turn emulsion downwards and float on surface of water for approximately 4 minutes.
Microscopic specimen
(4)
Lift specimen to contact emulsion until the latter covers the specimen.
(5) Dry in the dark and expose.
(6) Process emulsion while superimposed on specimen.
(7) Inspect autoradiograph when completed under microscope.

FIG. 7. Procedure for preparing autoradiograph using a stripping emulsion supported by gelatin

by chemical action or abrasion, as discussed later. This advantage is gained at the expense of resolution. It may also prevent direct contact between the photographic developer and the section; hence staining of tissue sections after processing is not possible.

In the Kodak Autoradiographic plate (as sold in England), the emulsion is reinforced by a gelatin layer 10 μ thick. With this material, the emulsion can be placed in direct contact with the specimen and processed through the gelatin. In both stripping materials, nuclear track emulsions of the type sensitive to about 80- to 100-kv electrons are used. Eastman Kodak Co. (U. S. A.) stripping film is now also available, on an experimental basis, with a permeable base. Another type of stripping emulsion suitable for autoradiography is the Ilford Special Halftone stripping plate. This consists of an emulsion mounted on a thin gelatin base which can be stripped from the glass support.

The procedure involved in the use of the Kodak Autoradiographic plate (*36*) is illustrated in Fig. 7. An area of the emulsion layer is cut out sufficiently to cover the entire specimen, with a margin at least a quarter of an inch all round. The microscope slide bearing the specimen containing the radioisotope is then placed on the bottom of a glass dish filled with distilled water. The emulsion and its gelatin support are stripped from the glass plate and placed on the surface of the water with the emulsion side underneath, facing the specimen. As it swells, the emulsion-gelatin composite first crumples and then stretches out flat. It should be permitted to swell for approximately 4 minutes and may then be lifted from the water by raising the slide underneath it.

The specimen with the superimposed emulsion layer should next be dried in a stream of cold air and placed in a light-tight box for exposure. Exposure may require from a few days to several weeks, depending on the activity of the radioactive isotope and its half-life.

Processing is then carried out with the emulsion layer in permanent contact with the specimen, using one of the conventional developers. Workers who wish to stain the specimen before use may require a developer which has a lower *p*H and a lesser tendency to wash stains or dyes out of the specimen. Amidol is such a developer.

Doniach and Pele (*38*) found a satisfactory technique of staining sections through the gelatin and emulsion after processing, provided the emulsion was

thin. The common nuclear stains used in cytology worked well, i.e., the various haematoxylins and methylene blue. Particularly good results were obtained using celestin blue and Mayer's haemalum.

A difficulty of fundamental importance in autoradiography is encountered if water-soluble tracers have to be employed in connection with the wet-stripping film technique described above. Russell, Sanders, and Bishop (*3*) described a method of locating water-soluble P^{32} in plant tissue. The tissue is dehydrated at $-70°$ C in alcoholic basic lead acetate, which precipitates the phosphate in situ. Before it is sectioned or placed in contact with the stripping emulsion, the tissue is embedded in wax. Other freeze-drying techniques are described by Wintering-ham, Harrison and Hammond (*35*), and by Harris, Sloane and King (*39*).

Another technique has been described recently by Belanger (*37*). His method is an improvement of his and Leblond's painting technique (*21*), mentioned earlier. A Kodak Matrix emulsion is painted over an unstained celloidin-coated histological section. After exposing and processing, the combined emulsion-celloidin-tissue preparation is inverted, and the section is stained. The result is called the "inverted autograph." The four advantages claimed are (1) possibility of mass production, (2) ability to work in semi-brightness, (3) retention in the sections of P^{32} present as mineral salt, and (4) easier and better staining.

Photographic artifacts and controls (*2, 40*). Photographic emulsions do not only respond to the action of photons and charged particles, but are also sensitive to an unlimited variety of chemical influences. The mere contact between certain elements, or inorganic and organic compounds, may lead to fogging of the emulsions at the area of contact. In addition to these chemical reactions, luminescent and pressure effects may also produce developable silver images in the emulsions.*

These artifacts, if not recognized as such, may easily lead to illusions in the interpretation of autoradiographs. To avoid this possibility, the use of control autoradiographs is an absolute necessity. Such a control has to be carried out with sections containing no radioactive material. Only if this control is negative, i.e., if no photographic action can be detected after a nonactive specimen has been placed in contact for the same exposure time as required for the genuine autoradiographs, is interpretation of the actual autoradiograph permissible. Several authors, notably Yagoda (*2*) and Boyd and Board (*40*), have drawn attention to this important point.

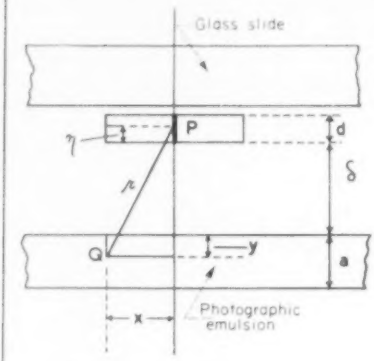
Boyd and Board have shown, e.g., that normal rat bone marrow diluted with clean dog serum caused blackening of a nuclear track plate when directly smeared on the emulsion surface and stored at about $-15°$ C for several days. Peripheral blood from the same rat diluted with the same dog serum did not blacken the plate. Several other effects of this kind have been traced by these authors.

If there is any doubt whether an effect is caused by chemical action or fluorescence, a thin sheet of quartz or a cover glass may be interposed between specimen and emulsion to permit the transmission of possible ultraviolet radiation.

To eliminate chemical artifacts, a thin impermeable film (such as can be made from Formvar, Kodak film lacquer, and others) may be interposed between specimen and emulsion.

Resolution. The problem of resolution attainable in autoradiography has

* EDITOR'S NOTE: A dry-mounting technique to avoid these difficulties was discussed in an article entitled "Method for Prevention of Leaching and Fogging in Autoradiographs" by A. I. Williams [NUCLEONICS **8**, No. 6, 10 (1951)].



d = specimen thickness
δ = distance between surface of specimen and emulsion
a = thickness of photographic emulsion
P = point in rod containing radioactive material
η = distance between P and surface of specimen
Q = point in photographic emulsion
y = depth of point Q in emulsion
r = distance between P and Q
x = length of perpendicular from Q to extension of rod

FIG. 8. Geometry of exposure for considerations on resolution (*38*)

been studied from a theoretical point of view by Doniach and Pelc (*38*) and experimentally by Stevens (*41*).

Theoretical. Let E be the exposure, N the total number of grains, n the number of developed grains, and ξ a factor depending on the characteristics of the photographic emulsion (such as grain size, grain sensitivity, the type and energy of radiation). Then, for moderate densities,

$$n = \xi NE \qquad (1)$$

Doniach and Pelc consider the distribution of developed grains in an emulsion due to the particles emitted from radioactive material in the form of a rod of length d having very small diameter and being perpendicular to the plane of the emulsion of thickness a having a distance δ from the specimen surface (see Fig. 8).

The effect of an element P on the point Q in the emulsion will be

$$dn = \frac{\xi NE\, dy\, d\eta}{4\pi r^2} \qquad (2)$$

On integration for the total length d of the rod and for the thickness of emul-

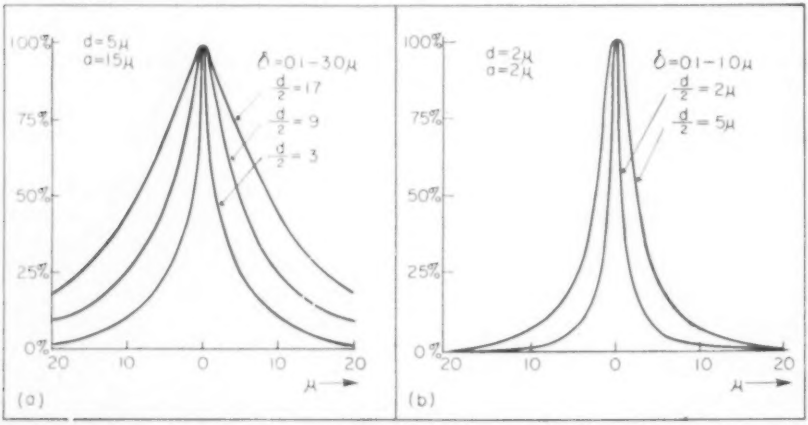


FIG. 9. Graphical results of computation by Doniach and Pelc (*38*) for different values of d (length of rod), δ (distance from specimen surface), and a (thickness of emulsion)

FIG. 10. Test chart enlarged from Kodak Maximum Resolution plate (*41b*)

FIG. 11. Autoradiograph of radioactive test chart containing I^{131} (*41b*)

sion a, this expression leads to

$$n = \int_{\eta=0}^{d} d\eta \int_{y=0}^{a} \frac{\xi EN}{4\pi r^2}\, dy$$

$$= \frac{\xi NE}{4\pi} \int_{\eta=0}^{d} d\eta \int_{y=0}^{a} \frac{dy}{(\eta + \delta + y)^2 + x^2} \quad (3)$$

The graphical result of the computation of this integral for different values of d, δ and a are shown in Fig. 9. The resolving power in terms of the half widths of the curves in Fig. 9 is denoted by $d/2$.

The curves in Fig. 9*a* indicate the relative spread of the number of grains at various distances between the photographic emulsion and specimen surface based on a given length of the rod (containing the radioactive substance) and emulsion thickness of 5 and 15 μ, respectively. It is found that the resolving power for gaps from 3–0.1 μ is improved from 17–3 μ. Figure 9*b* shows similar conditions for a rod length of 2 μ for an emulsion thickness of 2 μ. If the gap between specimen and emulsion is reduced from 1–0.1 μ the resolving power will be improved from 5–2 μ.

Pele and Doniach conclude from these results that the distance between photographic emulsion and specimen is of greatest importance and that optimum results may be obtained with a reasonably fine grained emulsion of about 4 μ thickness, using a technique that ensures contact better than 0.1 μ.

Experimental. By the method described by Stevens (*41*) for the objective measurement of resolution, a test chart, such as that used for determining the resolution of photographic lenses, is reduced photographically onto a Kodak (England) Maximum Resolution plate. This material permits a resolution of about 1,200 lines per millimeter. The chart shown in Fig. 10 is an actual enlargement of a silver image 1.3 × 1 mm in size on such a plate. This silver image is reconverted into a silver halide image. The halide is then converted to radioactive iodide (I^{131}).

Figure 11 shows a similar enlargement of an autoradiograph of the small iodine test chart. For the autoradiograph, the Kodak stripping emulsion was used.

From the known separation of the lines, the autoradiographic resolution obtainable has been found to be greater than 2.5 μ, which is in fair agreement

with the values theoretically derived by Doniach and Pelc. Resolution of the order mentioned can be attained only with thicknesses of specimens not exceeding 3–5 μ, since particles emitted at greater distances from the emulsion will have a greater divergence. Figure 12 illustrates how the resolution is affected if the distance between specimen and emulsion is increased.

This effect has been studied systematically by Stevens (*41*) by overcoating the charts with gelatin. Because the test chart image is confined to the surface of the emulsion layer of the chart, the resultant autoradiograph will show the conditions for radioactive material situated at a given distance below the surface of the section. As seen from Fig. 12, a separation of 3 μ produces a very marked loss of resolution.

The effect of resolution has also been stated by Stevens in terms of lines/mm which can be detected by different separations between radioactive material and emulsions using stripped experimental Process and Nuclear Track emulsions. These measurements are given in Table 2.

TABLE 2
Effect of Resolution
[Stevens (*41*)]

Emulsion type	*Thickness of separating layer*	*Resolution (lines/mm)*	*Line width*
Process	0 μ	95	5.3 μ
	3 μ	45	11.0 μ
	10 μ	24	20.8 μ
Nuclear Track	0 μ	220	2.3 μ
	3 μ	61	8.2 μ
	10 μ	35	14.3 μ

How the resolution changes with the use of other isotopes emitting electrons of shorter ranges has not been investigated systematically, as far as the author knows. According to Howard and Pelc (private communication), the resolving power with S^{35} is better than with P^{32}.

Although it may be assumed that shorter ranges of electrons might improve resolution, the effect of increased scatter of slow particles might nullify the advantage of the shorter ranges. This is so because most ranges (even those of the relatively slow electrons emitted by C^{14} and S^{35}) far exceed the thickness of a 5-μ emulsion.

Speed and exposure time (*5*, *36*, *42*, *43*). The sensitivity of photographic emulsions to charged particles and photons is of great importance and determines the exposure time required to obtain an autoradiograph for a given activity of the specimen. The limitations in speed of the photographic material, particularly if long-lived isotopes are to be used, might make it impossible in some cases to take an autoradiograph within a reasonable exposure time. This will depend largely on the permissible quantity of uptake of isotope by the specimen.

The exposure time depends largely on whether an autoradiograph of optical density or of a relatively small number of developed grains per unit area is required. Optical density is necessary if small magnifications are used, but, in the autoradiography of microspecimens, a small number of grains per unit area (or low grain density) is often sufficient.

Pelc and Howard recently found that, under very favorable conditions, as small concentrations as 10 grains per 100 μ^2 (above background) can be observed, if the number of background fog grains is low. The speed depends here on the minimum exposure needed to give a statistically significant grain count. The figure of 10 grains/100 μ^2 above background corresponds to 10^7 grains/cm^2.

Examples of autoradiographs with a low grain-density distribution and with optical density are shown in Fig. 13.

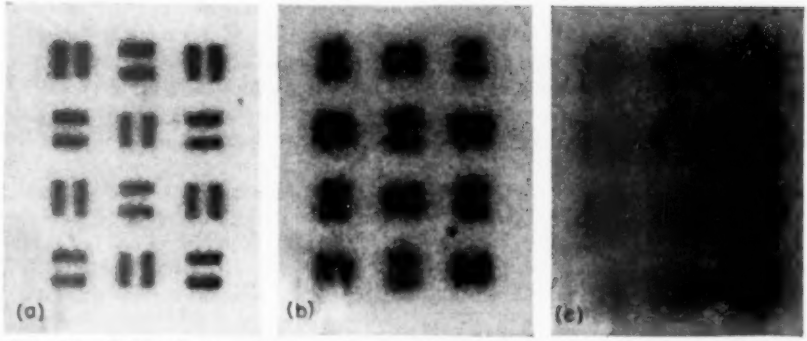


FIG. 12. Photomicrograph of an image corresponding to 56 lines/mm (8.9 μ line width) with (*a*) perfect contact, (*b*) 3 μ separation between emulsion and test chart, and (*c*) 10 μ separation

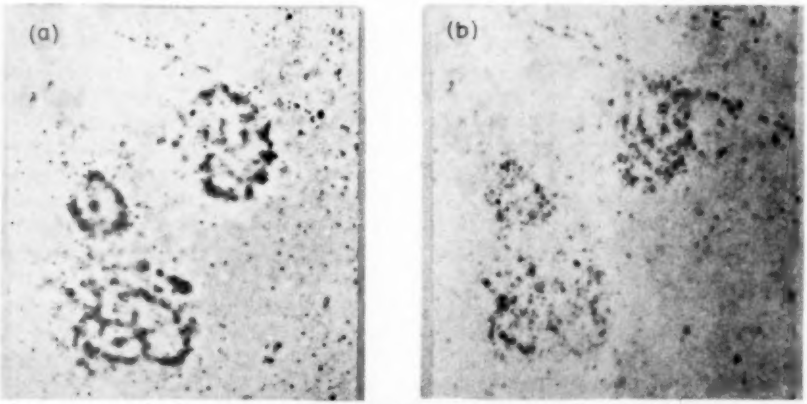


FIG. 13. (*a*) Phase contrast image of chromosomes, meiotic cell (dipletine) mouse testes, and autoradiograph superimposed (autoradiograph was of low grain density). (*b*) Optical-density autoradiograph of same field. Magnified 800 ×

The speed of a photographic emulsion to a given radiation is a complex function of several factors such as intrinsic grain sensitivity, size of grains, coating weight, concentration of silver bromide in gelatin, etc. In autoradiography, one is chiefly concerned with exposure to electrons and since the energy dissipation within a grain produced by slow electrons is greater than that produced by fast electrons, it can be assumed that the sensitivity of photographic emulsions increases with decrease of beta-ray energy.

If the interval between exposure and development is great, say, days or weeks photographic emulsions may exhibit latent image fading (*42*, *43*). It has been shown by several workers that this effect is strongly influenced by the humidity of the emulsion and the surrounding atmosphere. It appears that the presence of free oxygen enhances latent image fading. If the relative humidity is kept low in the surrounding atmosphere, latent image fading will tend to be at a minimum. Recent experiments with the Kodak (England)

Autoradiographic stripping plate have shown that a plate exposed for one week and treated under the recommended conditions revealed a loss of speed of about 30% due to fading.

The speed of a photographic emulsion to beta rays may be expressed in terms of the number of electrons per unit area incident on the emulsion to give a certain density. Speed values given by Berriman, Herz, and Stevens (*36*) for the Kodak Autoradiographic plate are quoted for I^{121} and P^{32} in Table 3.

The density of 0.5 was chosen as a reasonable upper limit of optical densities likely to be used in autoradiography.

To assess long exposure times using autoradiographic plates (nuclear track emulsions), commercial X-ray emulsions, because of their high sensitivity to electrons, can serve as a quick guide, as follows: The exposure with an X-ray emulsion can be done in about $\frac{1}{100}$ of the time needed to obtain the same density on a thin nuclear track plate. Bearing this in mind, one can then use X-ray emulsions to estimate necessary exposure times.

Quantitative evaluation (*36*). To estimate quantitatively the amount of radioactive substance present within a given volume of a section of specimen, it is necessary, first, to determine the number of grains rendered developable per incident particle.

For the case of electrons, this has been done by various workers for X-ray emulsions and for the Kodak (England) Autoradiographic stripping plate, using electrons emitted by P^{32}. Two different methods of approach have been used in estimating the grain yield per incident electron. In both cases the number of electrons incident per cm^2 of sensitive layer has been computed from the exposure time, knowing the absolute activity of the isotope per cm^2 in microcuries.

To estimate the number of grains rendered developable per cm^2, a count can be made under a microscope, using a small number of incident electrons and subtracting the number of fog grains as measured on an exposed control plate. Since grain counting of the very small grains of the autoradiographic emulsion is difficult and tedious, the number of grains rendered developable per cm^2 of emulsion has been computed from the measured optical density. Here a much greater number of incident electrons per cm^2 is required than in the first case. The mean projective areas of the grains have been determined by the electron microscope and were found to be 0.0625 μ^2.

The number (n) of grains affected can be estimated from Nutting's (1913) formula, $D = 0.4343\bar{a}n$, where D, the photographic density, equals $\log I_0/I_1$ and $\bar{a}$ is the mean projected area of the developed grains. A grain yield of 0.77 has been found for P^{32} electrons. Lamerton (private communication) counted the number of grains under a microscope and obtained, in a preliminary investigation using P^{32}, a value of 0.50 for the grain yield, which means that two electrons are required on the average to render one grain developable. The agreement is quite reasonable, considering the different methods of approach. Using S^{35}, Lamerton found a grain yield of 1.8.

Similar estimations have been carried out on X-ray emulsions, and a grain yield of unity was found using both the counting and the computation method.

A count of the number of developed grains per unit area in various regions of the autoradiograph may then be used (*a*) to evaluate the *absolute* concentration of the isotope if the grain yield is known, or (*b*) to evaluate the relative concentration without knowledge of the grain yield.

If the number of grains is low enough to be counted, their number is proportional to the activities of the radioactive

TABLE 3
Initial Activity and Number of Electrons Per Square Centimeter Required to Obtain a Density of 0.5 Above Fog Within Exposure of 10 Days (Kodak Autoradiographic Plate)

Isotope	*Maximum energy of electrons (Mev)*	*Initial activity* ($\mu c/cm^2$)*	*Electrons/cm²*
I^{131}	0.69	2.6×10^{-2}	0.56×10^9
P^{32}	1.7	5.5×10^{-2}	1.4×10^9

* If the number of electrons required to obtain a given density above fog for a given isotope is known, the initial activity in microcuries to produce this density in a given time is easily found from the equation:

$$(\mu c)_0 = \frac{n_e \lambda}{3.7 \times 10^4 (1 - e^{-\lambda t})}$$

where n_e is the number of electrons required, λ is the decay constant in sec^{-1}, and t is the time in sec.

tracer in the specimen. This follows from the linear relationship between exposure and the number of developed grains. For X-ray films, this relationship holds up even to optical densities of about 0.5 above fog for a single layer.

If autoradiographs of low grain density (10 grains/100 μ^2 above background) are carried out, the number of P^{32} electrons required per 100 μ^2 is 10 (assuming a grain yield of unity). Calculations show that the initial activity of P^{32} to obtain in 10 days 10 grains/100 μ^2 is only 3.9×10^{-10} μc.

Autoradiography by Particle Tracks

The advantages of track autoradiography (*39, 44–49*) over the method previously described are the possibility of working with still more minute quantities of radioactive material, the possible reduction of exposure time, and the production of a type of record that would be less liable to simulation by artifacts. It has often been stated also that the resolution may be improved by track autoradiography. This may be true but it has yet to be proved by experiment.

The final track autoradiograph is examined under the microscope so that tracks from charged atomic particles arising from a localized spot, say from the nucleus of a cell, can be traced to their origin. As mentioned earlier, very little work has been done on track autoradiography so far and this section will serve more to indicate the potentialities of the method than to present actual results obtained.

The mere recording of charged particle tracks in nuclear track plates is no longer a problem, but to apply this method successfully in the field of autoradiography, one difficulty has to be overcome. This involves preventing formation of unwanted background tracks caused by cosmic rays impinging on the emulsion or by the traces of radioactivity of the surrounding air or packing material. The accumulation of such tracks commences immediately after the manufacture of the plates and measurements have shown that about 10^4 electron tracks are recorded spontaneously in a 200-μ-thick emulsion per cm^2 per day. Hence even the use of such an emulsion within a few hours after manufacture will not remove this difficulty.

Two alternative methods may be used, however, to reduce the accumulation of unwanted tracks:

(1) A liquid emulsion can be coated onto the specimen directly by the research worker himself. No tracks will

be formed in the liquid emulsion while stored in a refrigerator, because the emulsion does not acquire its full sensitivity until it is coated and dry.

(2) The tracks already formed in the emulsion after coating may be eradicated before using the nuclear track emulsion. Several eradication techniques have been described in literature, the basic principle being to expose the emulsion to almost 100% relative humidity for several days (but not by bathing in water) and to dry the emulsion afterwards at a controlled low humidity. Not all eradication methods lead to a full restoration of the original sensitivity, but this will be required only for very fast electrons of energies close to and beyond 1 Mev. For recording electron tracks from, say, S^{35} or C^{14} (maximum energies 170 and 145 kv, respectively), an emulsion sensitivity up to 200-kv electrons may be sufficient.

FIG. 14. Alpha-particle track autoradiograph of the skin of a mouse containing polonium

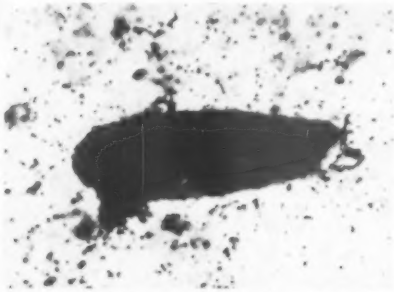


FIG. 15. Electron track autoradiography of *Paramecium caudatum* taken from a poured emulsion using culture containing P^{32} of 0.01 μc/ml activity

In many cases a few isolated background tracks may not seriously interfere with the interpretation of the results, particularly, if the interpretation is done on a statistical basis.

The potentialities of the method of track autoradiography are indicated by the following remarks taken from a paper by Harris, Sloane, and King (*39*): "Sections giving a Geiger-Müller beta-particle count of only 10 cpm/mm² of section give autoradiographs of excellent contrast with an exposure of a few hours, and by studying individual tracks instead of photographic density, the emission of as few as four beta tracks from a single *Colpidium* has been recorded with a three-hour exposure."

Examples of electron and alpha-track autoradiographs are given in Figs. 14 and 15. Electron track autoradiographs of C^{14}-activated blood cells were taken by Boyd *et al.* (*45*) in 1948, and of rat's liver section injected with C^{14}-labeled glycine (*44*) in 1950.

A specialized technique of track autoradiography was recently used by King, Harris, and Tkaczyk (*47*) who added the liquid emulsion to a culture of *Paramecium caudatum* containing P^{32}. See Fig. 15. The culture was washed by centrifuging several times before the emulsion was added. The emulsion containing the organisms was then poured onto a glass slide, rapidly dried by a current of air at a relative humidity of approximately 60%, and then exposed for 24 hours before processing. The evaluation of the tracks was done on a statistical basis by plotting the number of organisms against the track count per organism in a histogram.

Although the processing of track autoradiographs does not require any specialized methods other than those

recommended by the plate manufacturers, coating thicknesses exceeding 100 μ need special treatment to obtain uniform development throughout the depth of the emulsion. In those cases, a so-called temperature cycle development has been introduced (*48*). The basic idea of this type of processing is to presoak the emulsion in the developer for about 20 minutes at a low temperature, say 5° C, and then gradually warm up the developer to room temperature, where development occurs in the usual way. At the low temperature, the developer penetrates to the bottom of the emulsion, but its action is reduced.

* * *

In connection with publication of Figs. 7–15, the author wishes to acknowledge the courtesy of the following: Kodak Ltd., London (Fig. 7); British Journal of Radiology *(Figs. 8–12); Dr. S. R. Pelc, Hammersmith Hospital, London (Fig. 13); Dr. L. F. Lamerton, Royal Cancer Hospital, London (the mouse skin preparation containing Po is due to Prof. Kreyberg, Universitets Institutt for Patologi, Oslo) (Fig. 14); and J. E. Harris and D. T. King, University of Bristol (Fig. 15).*

BIBLIOGRAPHY

1. A. Lacassagne, J. Lattes, *Compt. rend. soc. biol.* **90,** 352 (1924)
2. H. Yagoda, "Radioactive Measurements with Nuclear Emulsions" (John Wiley & Sons, Inc., New York, 1949); also NUCLEONICS **4,** No. 5, 134 (1949) and **2,** No. 5, 2 (1948)
3. R. S. Russell, F. K. Sanders, O. N. Bishop, *Nature* **163,** 639 (1949)
4. D. I. Arnon, P. R. Stout, F. Sipos, *Am. J. Botany* **27,** 791 (1940)
5. A. M. MacDonald, J. Cobb, A. K. Solomon, D. Steinberg, *Proc. Soc. Exptl. Biol. Med.* **72,** 117 (1949)
6. J. Cobb, A. K. Solomon, *Rev. Sci. Instr.* **19,** 441 (1948)
7. D. Steinberg, B. Selverstone, *Proc. Soc. Exptl. Biol. Med.* **74,** 304 (1950)
8. D. H. Copp, D. Axelrod, J. G. Hamilton, *Am. J. Roentgenol. Radium Therapy* **58,** 10 (1947)
9. H. F. Sherwood, *Rev. Sci. Instr.* **18,** 80 (1947)
10. N. M. Shapiro, *Revs. Mod. Phys.* **13,** 58 (1941)
11. C. F. Powell, G. P. Occhialini, D. L. Livesey, L. V. Chilton, *J. Sci. Instr.* **23,** 102 (1946)
12. R. W. Berriman, *Nature* **161,** 432 (1948); *Nature* **162,** 992 (1948)
13. R. H. Herz, *Nature* **161,** 928 (1948); *Phys. Rev.* **75,** 478 (1949)
14. J. Rotblat, "Progress in Nuclear Physics," Vol. I, pp. 37–73 (Butterworths-Springer, Ltd., London, 1950)
15. P. Demers, *Can. J. Research* **25A,** 233 (1947)
16. M. A. S. Ross, B. Zajac, *Nature* **162,** 923 (1948)
17. B. Zajac, M. A. S. Ross, *Nature* **164,** 311 (1949)
18. G. E. Bell, *Brit. J. Radiology* **9,** 578 (1936)
19. E. E. Smith, *Phot. J.* **83,** 303 (1943)
20. C. P. Leblond, *Stain Technol.* **18,** 159 (1943)
21. L. F. Belanger, C. P. Leblond, *Endocrinology* **39,** 8 (1946)
22. K. M. Endicott, H. Yagoda, *Proc. Soc. Exptl. Biol. Med.* **64,** 170 (1947)
23. T. C. Evans, *Proc. Soc. Exptl. Biol. Med.* **64,** 313 (1947)
24. P. Demers, V. Fredette, *Bull. Am. Phys. Soc* **22,** No. 3, 20 (1947)
25. J. G. Hamilton, M. H. Soley, K. B. Eichorn, *Univ. Calif. Pubs. Pharmacol.* **1,** 339 (1940)
26. T. C. Evans, *Radiology* **49,** 206 (1947)
27. A. V. Grosse, J. C. Snyder, *Science* **105,** 240 (1947)
28. S. R. Pelc, *Nature* **160,** 749 (1947)
29. G. A. Boyd, *J. Biol. Phot. Assoc.* **16,** 65 (1947)
30. A. M. MacDonald, J. Cobb, A. K. Solomon, *Science* **107,** 550 (1948)
31. G. A. Boyd, A. I. Williams, *Proc. Soc. Exptl. Biol. Med.* **69,** 225 (1948)
32. D. A. Heller, J. G. Hamilton, p. 817, "Medical Physics, Vol. 2," Otto Glasser, editor-in-chief (The Year Book Publishers, Inc., Chicago, Ill., 1950)
33. D. W. Jenkins, C. C. Hassett, NUCLEONICS **6,** No. 3, 5 (1950)
34. A. N. Barker, H. G. W. Richardson, N. Feather, *Research* **3,** 431 (1950)
35. F. P. W. Winteringham, A. Harrison, J. H. Hammond, *Nature* **165,** 149 (1950)
36. R. W. Berriman, R. H. Herz, G. W. W. Stevens, *Brit. J. Radiology* **23,** 472 (1950)
37. L. F. Belanger, *Anat. Record* **107,** 149 (1950)
38. I. Doniach, S. R. Pelc, *Brit. J. Radiology* **23,** 184 (1950)
39. J. E. Harris, J. F. Sloane, D. T. King, *Nature* **166,** 25 (1950)
40. G. A. Boyd, F. A. Board, *Science* **110,** 586 (1949)
41. (*a*) G. W. W. Stevens, *Nature* **161,** 432 (1948); (*b*) also *Brit. J. Radiology* **23,** 723 (1950)
42. H. Yagoda, N. Kaplan, *Phys. Rev.* **71,** 910 (1949)
43. G. Albouy, H. Faraggi, *J. phys. radium* **10,** 105 (1949); also *Compt. rend.* **228,** 68 (1949)
44. G. A. Boyd, H. Levi, *Science* **111,** 58 (1950)
45. G. A. Boyd, G. W. Casarett, K. I. Altman, T. R. Noonan, K. Solomon, *Science* **108,** 529 (1948)
46. I. H. Ford, *Nature* **167,** 271 (1951)
47. D. T. King, J. E. Harris, S. Tkaczyk, *Nature* **167,** 273 (1951)
48. C. C. Dilworth, G. P. S. Occhialini, R. M. Payne, *Nature* **162,** 102 (1948)
49. F. E. Hoecker, P. G. Roofe, *Radiology* **56,** 89 (1951)

An Extrapolation Chamber: Construction and Use

Surface and depth-dose rates of betas can be measured with this precision chamber. Modification to allow measurement over a wide pressure range extends the use of the instrument to higher ionization currents and to backscatter studies

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THE EXTRAPOLATION chamber method developed by Failla (*1, 2*) has proved to be an excellent means of measuring surface and depth-dose rates of beta radiation. The mechanical requirements are such that many variations of construction are possible. In this paper, an attempt is made to show one variation from the conventional extrapolation chamber and also to show its diverse uses.

Ideally, the measurement of radiation dose rate at a surface would be accomplished by measurement of the rate of ionization in a well-defined volume of air of infinitesimal thickness adjacent to the surface. Since such a measurement is impractical, the extrapolation chamber is designed to provide a movable collecting electrode and guard ring which can be kept parallel to the emitting surface. The ionization measurements can be made in decreasing volumes which approach this situation of ideality.

From these measurements one gets, by extrapolation, the limiting ionization per unit volume as the electrode separation approaches zero.

Instrumentation

The conventional extrapolation chambers used in this laboratory are basically the same as those described by Sheppard and Abele (*3*). Some minor changes have been made in the original design to insure parallelism of the electrodes and to facilitate measurement of the chamber volume. A cross sectional view of this type of chamber is shown in Fig. 1.

The mechanical arrangement must be such that the two surfaces of the collecting volume remain parallel at all times and such that they can be so adjusted that the plate (or electrode) separation is known with a high degree of accuracy. Separation and parallelism of the electrodes are determined by a metric-micrometer depth gage. The movable shell of the chamber is threaded with a pitch of 1 mm. The circumference is divided by an engraved scale into 40 divisions.

An undistorted electrical field is necessary for ion collection. Very close separation of the guard ring and the collector help to accomplish this. The collector and guard rings are threaded so that they screw down tightly to form a uniform flat surface, and are separated by a space of 0.005 in.

The output voltage of the chamber is measured across one of six resistors ranging from 10^{13} ohms for very small currents down to 10^{10} ohms for larger currents. In using the 10^{12}- and 10^{13}-ohm resistors, a shielded line filter on the collecting voltage supply has proved useful. Measurements are made by a

null method using a vibrating-reed electrometer, the output of which is indicated on a recorder. The compensating emf in millivolts, as measured on a potentiometer, is used to compute the rate of ionization. Cyclic reversal of collecting voltage was used in all beta measurements to compensate for the charge carried by the primary particles. The average of the values thus obtained are used.

Two chambers of this type, with collector electrodes of area 3.142 cm² and 5.000 cm² respectively, are in use at the present time. While the higher sensitivity of the larger collector is often advantageous, the difficulty of obtaining parallelism is increased. The smaller collector is more convenient where increased sensitivity is not required.

Twelve sets of collectors and guard rings are available for each chamber. Some of these are of plastic, one is carbon, and the remainder are of metals whose atomic numbers range from 4 to 92.

Variable-Pressure Chamber

For many purposes it is advantageous to have the extrapolation chamber in an airtight enclosure in which measurements can be made at pressures varying from near vacuum to several atmospheres. Such an arrangement permits the use of higher ionization currents with high-intensity sources, and measurements in vacuo for studies of backscatter and other phenomena. For such purposes a conventional extrapolation chamber has been redesigned and enclosed in an airtight case made of brass and Lucite, as shown in Figs. 2 and 3.

The Lucite top permits a full view of the thermometer inside the pressure chamber. The chamber is designed to contain a polyethylene lining to minimize backscattering coming from the chamber wall.

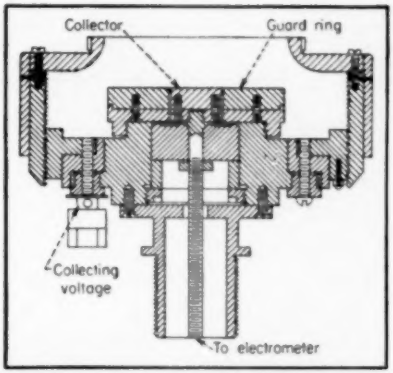

FIG. 1. Cross-sectional view of extrapolation chamber

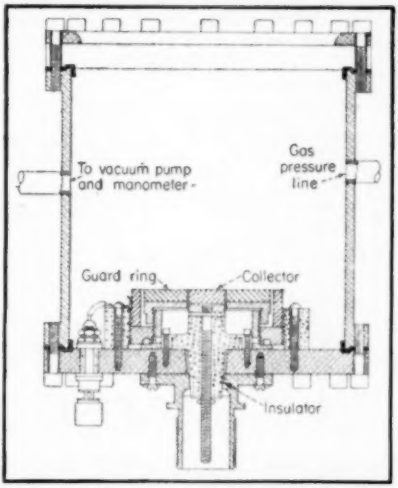

FIG. 2. Cross-sectional view of variable-pressure chamber

If only sources having effectively infinite thickness are to be used, the size of the pressure chamber could be reduced from 5½ in. in diameter and 6 in. in height to 4 in. in diameter and 3 in. in height. Also, the window may be omitted, as ready access can be had from the top.

Considerable skill is required to get an insulator through the case so that it will not move when pressure is applied from either direction; such movement

FIG. 3. Variable-pressure chamber mounted on resistor box and vibrating-reed electrometer

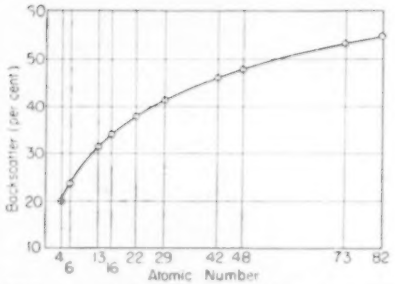

FIG. 4. Backscatter of betas from P^{32} as a function of atomic number

would affect the very critical electrode separation.

Measurement of dosage rate. The response of the variable pressure chamber has been studied with air pressures ranging from 10^{-3} mm of Hg to 7 atmospheres and with collecting voltages from 0 to 2,500 volts. As expected, the measured ionization is proportional to the pressure of the gas.

For the measurement of dosage rate, the electrode separation is adjusted to a value in the range for which the measured ionization is known to be proportional to the separation (1 mm or less). The chamber is evacuated and filled to the desired pressure with dry air (or other gas).

The rate of ionization is computed by using the equation

$$I = 3{,}600 \text{ sec/hr} \times 3 \times 10^9 \text{ esu/coulomb} \times E/RV$$

where I = rate of ionization (esu/cm³/hr), E = electrometer potential (volts), R = resistance (ohms), and V = volume of air from which ions are collected (cm³).

For beta and gamma radiation, I, in esu/cm³/hr, is numerically equivalent to the dosage rate measured in rep/hr. For alpha radiation the equivalent number of rep/hr is obtained by multiplying the number of esu/cm³/hr by 1.16 (*4*, *5*).

When sources exceeding saturation thickness are used, backscatter from the pressure-chamber walls need not be considered. When the source is mounted on a thin material such as Zapon or rubber hydrochloride, the backscatter from the pressure chamber must be taken into account. Backscatter at atmospheric pressure can be determined experimentally by removal of the pressure chamber. For beta radiation of 1.7-Mev maximum energy, backscatter was found to be 1.3%. By lining the chamber with polyethylene ⅛ in. in thickness, the backscatter was reduced to an insignificant value. Backscatter in a near vacuum cannot be measured directly, but it was shown that the response to 1.7-Mev beta radiation with a pressure of 10^{-3} mm Hg was decreased 2.5% when the chamber was lined with polyethylene. The lining did not interfere seriously with the obtaining of a vacuum sufficiently good to stop ionization. As was previously stated, this lining would not be necessary for sources of infinite thickness.

Other uses. While the extrapolation chamber was designed for the measurement of dose rates, the variable-pressure modification permits its use for other types of measurement. This

modification is particularly useful for studies of the reactions of primary beta particles with various materials.

Figure 4 shows measured backscatter of beta radiation from the elements from beryllium to lead, for the geometry used in this particular set of measurements. The backscatter depends upon the energy of the radiation and upon the geometry of the chamber. These measurements were made at atmospheric pressure.

Figure 5 shows the dependence of the measured electron current upon the atomic number of the collecting electrode. The sources of the beta radiation are P^{32} and S^{35}; collection is made at near vacuum with a potential of 90 volts. The source mounting for the measurements shown in Figs. 4 and 5 is the same as that described for Fig. 6.

The dependence of measured current on the potential of the collector is illustrated in Fig. 6 for a different set of conditions. Here S^{35} is used as the source of beta radiation; the collecting electrodes are of beryllium and lead, and the potential of the collecting electrodes is varied from -10 to $+10$ volts. The ordinates represent the increase and decrease in measured current referred to that obtained with zero collecting voltage. When the chamber is not evacuated, these effects are masked by the larger currents resulting from the ionization of the air.

The S^{35} used for the measurements shown in Fig. 6 was deposited on a very thin film of rubber hydrochloride. In each case the material of the guard ring was the same as that of the collecting electrode.

Zero collecting potential was established by reversal of the leads to the chamber with no effect on the electrometer. The first 1½ volts of collecting potential were taken from a potentiometer, and the balance (up to 10 volts) from a carefully measured voltage supply. Above about 20 volts no

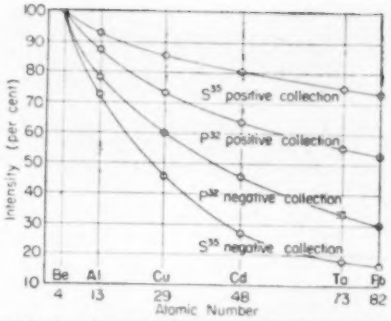

FIG. 5. Depreciation of electron current from P^{32} and S^{35} as a function of atomic number of electrode. Intensity with Be collector set at 100%. Pressure is 10^{-3} mm Hg

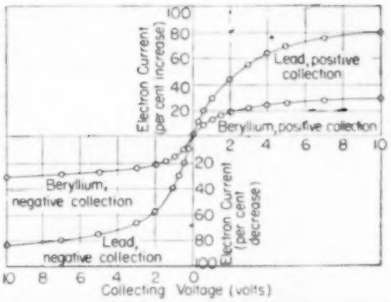

FIG. 6. Dependence of electron current from S^{35} on collecting voltage for Be and Pb electrodes. Pressure is 10^{-3} mm Hg

rapid change in the collected current was apparent; from that point up to 2,500 volts, the current continued to change slowly.

It will be noted that the increase in electron current with increase in the positive potential of the collecting electrode, and the decrease in electron current with increase in the absolute magnitude of the negative potential of the collecting electrode, are not symmetrical.

Measurements using P^{32} and Sr^{90} as sources of beta radiation gave the same sort of results, except that the difference in rate of collection for the beryllium

(Continued on page 94)

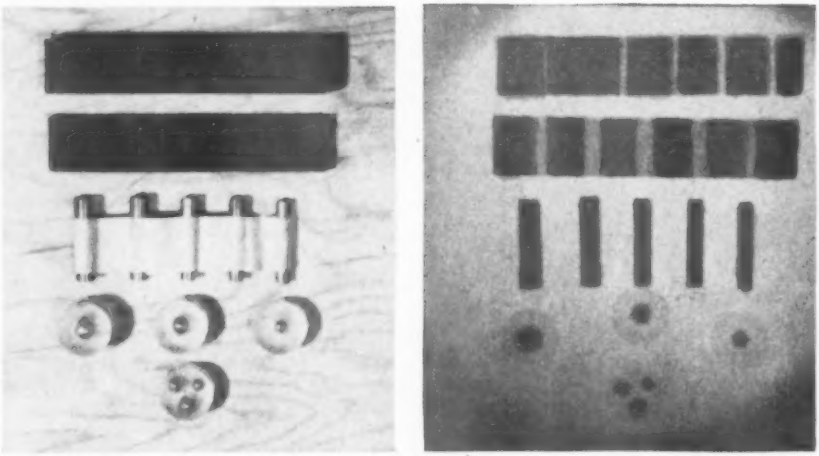

Image (right) of objects (left) as seen on fluoroscopic screen using gamma rays from iridium-192 source in work done at the National Research Council in Canada. Photograph at right was taken by hour-long exposure with Super-XX film and is one of the first ever taken of a fluoroscopic image produced by gamma rays

FLUOROSCOPY WITH GAMMA RAYS

Until now, there have been limitations on use of gamma rays in fluoroscopy. Described here is a 14-mm^3 Ir^{192} source from the Chalk River reactor, which shows promise for such work

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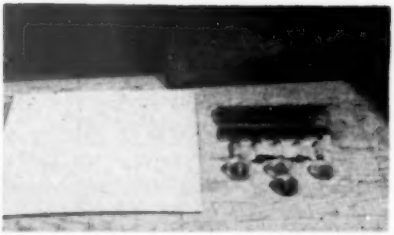
ALTHOUGH the gamma rays from radium and from some radioisotopes have been employed for the radiography of steel and other metals, they have not, up till now, been used for fluoroscopy.

As part of an investigation into the radiographic characteristics of iridium-192 (*1*), a source of high intensity was prepared. It was a cylinder of iridium sponge, compressed into a pellet 3 mm in diameter and 2 mm high, at the center of an aluminum cylinder 1 cm in height and in diameter, and it had a radiation output of 1.89 r/hr at 1 meter.

Because this source was small enough to approximate a point source for an object 20 or 30 cm away from it, and since it had high output of gamma rays, it seemed worthwhile to see whether or not it could be used for fluoroscopy.

There are a number of reasons why gamma rays from most radioactive materials seem unsuitable for fluoroscopy:

Until quite recently, the radiation output of gamma-ray sources has been very low. A radium pellet of 500 milli-



View of objects seen in the photographs on the opposite page. The fluoroscopic screen is lying at the left. Lead shielding can be seen in the background. The objects are penetrameters made to test the sensitivity of the gamma-ray fluoroscopy method. They are steel cylinders, steel plates with drilled holes, and plastic disks with ball bearings

grams was considered a large source, yet the radiation output 1 meter from this source is only about 0.4 roentgens per hour. Sources equivalent to 3 or 4 gm of radium are now available for radiographic use, but even with these sources the intensity at a meter does not exceed 2 or 3 r/hr. This intensity seems very low when compared to the usual intensities in an X-ray beam, which may be of the order of 5 to 10 r/*min* at 1 meter from the target. Because these gamma-ray intensities seemed so low, fluoroscopy was not considered or was dismissed as impractical.

Larger gamma-ray sources than those mentioned above have been produced, but for fluoroscopy a very small source of radiation is needed so that sharp shadows of the internal structure will be cast on the fluorescent screen. The sources of gamma rays of high intensity which were produced, were physically large, and could not be considered, even approximately, as point sources. Sharp images could not be expected from them.

Two of the most common sources of intense gamma rays are cobalt-60 and radium. Their gamma rays are of high energy and are so penetrating that only a small change in the intensity of the beam reaching the screen, and hence in the luminance of the image, would be expected for a relatively large change in the thickness or density of the object under examination. The contrast in the fluoroscopic image would be correspondingly low.

Another aspect is that gamma rays passing through matter generate secondary radiations of lower energy which are scattered in all directions from the irradiated areas. The fluoroscopic screen responds more efficiently to these radiations than to the more energetic quanta. Therefore, the secondary radiation may be expected to produce a general diffuse illumination on the screen which would tend to obscure the details in the image produced by the primary beam.

A factor in favor of the Ir^{192} source mentioned above was that its gamma rays, having energies between 200–600 kev, with the rays of maximum intensity at about 315 and 467 kev, are much lower in energy than those of radium or cobalt. Thus, a small change in the thickness of an object will make a much greater change in the intensity transmitted than would be the case for the rays from cobalt-60 or radium.

Test with Iridium Source

The iridium source, in its shipping container, was placed in a dark room, and a Patterson Type B-2 fluoroscopic screen was held about 30 cm above it. A few minutes were allowed for the eyes to become adapted to the dark; then the stopper was removed. A faintly illuminated circular area could be seen on the screen. After a few more minutes, when the eye adaptation had become better, the screen appeared to glow quite brightly. A steel plate and the head of a hammer cast clearly visible shadows on the screen. Two ¼-inch steel plates and a ½-inch one, stacked on each other so that they par-

TABLE 1
Flat Penetrameters

No.	*Length (inches)*	*Width (inches)*	*Thickness (T) (inches)*	*Hole diameter (multiples of thickness)*
1	1.5	0.50	0.040	2*T*, 3*T*, 4*T*
2	1.0	0.75	0.060	*T*, 2*T*, 3*T*
3	1.0	0.75	0.080	*T*, 2*T*, 3*T*
4	1.5	0.75	0.125	2*T*, 3*T*

tially overlapped in step fashion, could be distinguished from each other. A 25-cent piece could be seen faintly on the ½-inch plate. When the cast lead plug was replaced in the shipping container, it was observed that the plug must have a center-line shrinkage cavity, as radiation was still reaching the screen through the plug and producing a bright spot on its axis.

These preliminary trials showed that fluoroscopy with iridium gamma rays might be more practicable than had been thought, and a further investigation was undertaken.

Method and Scope of Investigation

The source, in a lead container, was moved to a room which could be more completely darkened, and the container was fitted with a lead collimating cone, so that a defined beam was directed vertically upward.

The container was mounted so that the source was about 20 cm below a plywood table top, and a piece of masonite, ¼ inch thick, was supported above the table top, and parallel to it, in such a way that the distance between the table top and the top of the masonite, and hence between the source and the top of the masonite, could be varied. A fluorescent screen was placed on the masonite. Test objects, sliding on the table top, could be moved under the screen and could be seen on it.

Rough tests indicated that the intensity after passing through an inch or more of steel was still adequate to produce an easily visible illuminated area on the screen. The internal metal structure of a telephone handset could be seen, metal objects packed in a box of lighter material could be located, steel screws and nails were visible in a piece of wood, and steel balls could be found in a brass box with walls that were ¼-inch thick.

More exact tests were made to determine the smallest thickness of steel which could be seen in the direct beam, and on various thicknesses of steel plates, and to find out how the radiation intensity at the screen varied with source-to-screen distance and with the thickness of steel placed in the beam. The luminance of the screen for different source-to-screen distances, and for different steel thicknesses in the beam, was measured. Several types of fluorescent screen were compared in luminance. The details of the measurements are given below.

Sensitivity

In radiography, the sensitivity of the technique used is often measured by finding, for each thickness of material radiographed, the smallest additional thickness of the same material, having a standard size and shape, which can be detected. These standard pieces, called penetrameters, may be chosen to be flat, cylindrical, or spherical. Those most commonly used for this purpose are flat, rectangular pieces, and are pierced by three holes of different diameters, so that some indication of the

sharpness of the radiograph is obtained from the visibility of these holes.

To get sensitivity data at this laboratory, two sets of penetrameters were used. The first set consisted of flat pieces of steel, of four thicknesses, each drilled with two or three holes. The diameters of the holes were multiples of the thickness of the piece in which they were drilled. Data on these are given in Table 1. The second set consisted of round rods, each 1.5 inches long, and of ten different diameters, the smallest rod being 0.091 inch and the largest 0.375 inch in diameter.

With the screen 4.0 cm above the table top, and 25.5 cm from the source, each set was placed in turn in the beam, first on the table top, and then successively on pieces of steel of thickness 0.25, 0.50, and 0.75 inch. Three observers noted the smallest penetrameter which could be seen, and in all cases their observations agreed. The results are summarized in Table 2.

The steps in size, particularly in the flat penetrameters, are too large, and the range in thickness is not great enough, to draw very accurate conclusions. As is to be expected, the flat pieces are more easily seen than the round bars, probably because of their sharp edges. Even for the flat bars, the smallest additional thickness that can be seen on the steel is about 25%, as compared to the 2%, or better, that can be seen in a radiograph with the same source of radiation. It would appear that this method of examination will not show the fine details of structure.

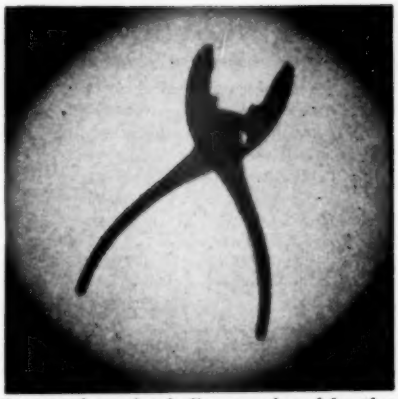


Image of a pair of pliers produced by the gamma-ray fluoroscopy method using an iridium-192 source. Graininess is due both to the screen and to the negative from the 35-mm Plus-X film on which the picture was taken

Radiation Intensity

The radiation output of the source was measured at 1 meter from it, using

TABLE 2
Visibility of Penetrameters

Steel thickness (inches)	*Smallest penetrameter which can be seen*			
	Flat pieces		*Round bars*	
	No.	*Thickness (inches)*	*No.*	*Thickness (inches)*
0	1	0.040 (holes not clear)	1	0.091
0.25	2	0.060 (holes not clear)	2	0.129
0.50	4	0.125 (holes clear)	3	0.156
0.75	none	.....	4	0.188

TABLE 3
Radiation Intensities at Screen Positions

Distance above source (cm)	*Intensity (r/min)*
21.5	0.72
25.5	0.51
27.4	0.46
32.4	0.31
100.0	0.032

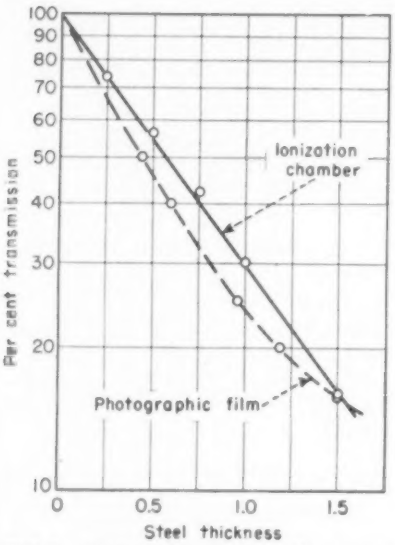


FIG 1. Comparison of absorption curves as measured by photographic film and by ionization chambers

a Victoreen 0.25-r chamber. It was found to be 31.5 mr/min or 1.890 r/hr.

To find the intensity of the radiation at the different positions occupied by the fluoroscopic screen, measurements were made at each position with Baldwin-Farmer ionization chambers, types BD-2 and BD-11. The results are given in Table 3.

These intensities, while still low compared to X-ray intensities, are much higher than those which have been usual in gamma-ray applications. Calculation shows that they are quite consistent with those expected from the inverse-square law.

The variation of intensity at the screen, with increasing thickness of steel absorber, was measured at the screen for screen-to-source distances of 25.5 and 27.4 cm. The results are given in Table 4.

The absorption curve found in this way is plotted as the solid line in Fig. 1; it differs from that found earlier with photographic film (*1*) which is shown as a dotted line. The present curve is nearly linear, and shows a half-value layer of 0.58 inch of steel, and an absorption coefficient μ of 1.2 per inch or 0.47 per centimeter.

The difference in the curves is probably due to the different proportions of primary and secondary radiation recorded by the film and ion chambers.

TABLE 4
Variation of Intensity with Thickness of Steel Absorber

Steel thickness (inches)	*Intensity at 25.5 cm from source*		*Intensity at 27.4 cm from source*	
	r/min	*Per cent of initial intensity*	*r/min*	*Per cent of initial intensity*
0	0.51	100	0.46	100
0.25	0.38	73	0.34	74
0.50	0.30	58	0.25	54
0.75	0.22	42	.....	...
1.00	....	...	0.14	30
1.50	....	...	0.073	16

Luminance

The luminance measurements, which will be described below, were made with a low luminance meter with a comparison field at 2,360° K. The meter was mounted at an angle of about 60 degrees from normal to the screen in all cases. The luminance was checked at about 30 degrees and there appeared to be no appreciable change in the luminance with the angle of observation.

Measurements of the luminance of the Patterson B-2 screen were made with the screen at various distances from the source. The distances and the luminances are given in Table 5.

TABLE 5
Luminance of Screen at Various Distances from Source

Distance from source (cm)	*Luminance of screen (microlamberts)*
21.5	9.6
25.5	7.3
27.4	6.2
32.4	5.3
42.5	2.9

These luminances are all very low, much lower than those used in medical and industrial fluoroscopy. Eye adaptation periods of 30 minutes were necessary for these experiments, and the room used had to be completely free of light leaks. It was found that illumination from the usual X-ray darkroom safelights, having Wratten 6B filters, could be tolerated, if the lights were used to produce a faint, general, red illumination and were not directed toward the observer.

By comparing Tables 3 and 5, one can see that the measured luminance does not vary directly with intensity. This is so because the luminance measurements are dependent on the sensitivity of the eye, which is not uniform with luminous flux at this low level. Also, the luminous flux may not be directly proportional to radiation intensity.

In the preliminary measurements, it was observed that the first ¼ inch of steel appeared to make a much greater difference in luminance than did successive equal thicknesses. To confirm this, measurements were made of the luminance of the B-2 screen with no steel and with 0.25, 0.50, and 0.75 inches of steel between the source and the screen which was 25.5 cm from the source. Measurements were also made of the luminance of this screen with the screen at 27.4 cm from the source and with 0.25, 0.50, 1.0 and 1.5 inches of steel between the source and the screen. In each case, the bottom of the steel plate, or plates, was on the table top 21.5 cm from the source. The measurements are given in Table 6.

In agreement with the visual obser-

TABLE 6
Measured Luminance of Screen with Steel Absorbers in the Beam

	Source-screen distance 25.5 cm		*Source-screen distance 27.4 cm*	
Steel thickness (inches)	*Luminance (microlamberts)*	*Per cent*	*Luminance (microlamberts)*	*Per cent*
0	7.3	100	6.2	100
0.25	4.4	61	4.0	63
0.50	4.1	56	3.2	52
0.75	3.1	43	...	...
1.00	...	...	1.9	30
1.50	...	...	1.1	18

vation, the drop in measured luminance, brought about by the first steel absorber, is much greater than that produced by the others, and is greater than the change in the measured intensity.

Luminance of Various Screens

It was felt that some information about the most suitable type of fluorescent materials to use with gamma rays might be gained by a comparison of the luminance of various types of screens. All measurements were made with the screens at 25.5 cm from the source. The gamma-ray intensity at this distance from the source is 0.48 r/min. The results of the comparisons of the screens are given in Table 7.

Since data published by Chamberlain (*2*) on the luminance of screens for X-ray fluoroscopy refer to the earlier Patterson Type B screen, measurements were made of the luminance of the B screen which was on hand. The luminance of the B-2 screen which had been used up till now was measured, as was that of a second B-2 screen.

At the level at which these measurements were made, 32.4 cm above the source, the luminances for the B screen, the B-2 screen, and second B-2 screen, were 2.2, 5.3, and 4.4 microlamberts, respectively. The B screen is much lower in luminance than either of the B-2 screens, and by a much greater factor than suggested by Chamberlain and Henny (*3*), and there is an appreciable difference between the two B-2 screens.

Discussion

The penetrameter sensitivity achieved in fluoroscopy with iridium gamma rays is not nearly as good as that which can be attained in radiography with the same radiation, nor is it even as good as that which can be obtained in X-ray fluoroscopy of comparable thicknesses of steel. This may be attributed to the high energy, and the consequent low absorption of the radiation, and to the low radiation intensity and the resulting low luminance of the screen.

TABLE 7
Comparison of Types of Screens

Type of screen	*Luminance of screen (microlamberts)*
Patterson B-2	7.6
Eastman Kodak Industrial H, Back screen	3.1
Eastman Kodak Industrial H, Front screen	2.3
Patterson Industrial 245, Thick type	2.2
Eastman Kodak Ultra Speed, Back screen (2686)	1.3
Eastman Kodak Fine Grain, Back screen (2986)	0.95
Eastman Kodak High Definition, Back screen (2018)	0.59
Patterson Hi-Speed	0.38
Patterson Detail	0.38
Patterson Par-Speed	<0.38

Nevertheless, fluoroscopy with gamma rays has been accomplished, and it may have useful applications. The compactness of the source, and its freedom from reliance on power lines, are important advantages.

A sensitivity which allows the detection of a flat piece of steel the thickness of a dime, and of a round rod less than a tenth of an inch in diameter, is adequate for many purposes. Better sensitivity may be obtained with sources of greater intensity, and with sources whose rays are less penetrating.

If it were possible to develop screens which were more efficient in converting gamma rays into visible light, the luminance of the screen, and the sensitivity of the method, would be enhanced.

Some improvement in the sharpness of the image formed on the screen could be gained by using a larger source-to-screen distance, but this would require

an increase in source strength, and hence, for a given specific activity of iridium-192, an increase in source size.

Because of the high self-absorption of the rays in the source itself, the increase in absorption with increasing dimensions of the source would soon outweigh any gain in intensity due to the increase in the volume of active material. This self-absorption has been discussed by Dixon (4).

The large drop in measured luminance, produced by the first steel plate, might be thought to be a physiological effect associated with the variation in response of the eye to color at that particular level of illumination. It is about here that change-over from rod to cone vision takes place, and the color of the fluorescent screen is not the same as that of the standard light source against which the instrument is calibrated.

This is not consistent, however, with the data of Table 5, where such deviations from the inverse-square law as do occur, measured by the product of luminance and distance squared, are in the direction which would indicate an overestimation, rather than an underestimation, of the lower luminances. The effect may be due to the absorption in the steel of the soft components of the radiation, since the screen responds more efficiently to these than it does to the harder ones.

Of the screens whose luminance was measured, the Type B-2 produced more than twice the luminance of the Type B screen, and was much superior in luminance to any of the others. There was a marked difference between the two B-2 screens; no reason is known for this. The other screens were intended for radiography rather than fluoroscopy, and were designed to produce the maximum response in the photographic plate rather than in the eye.

* * *

We would like to acknowledge most gratefully the assistance given by Miss E. G. Mayo and Mr. C. L. Sanders of the Photometry and Colorimetry Laboratory of the Physics Division, in measuring screen luminances, and by Miss Helen Chabun and Miss Edith Ferguson of this laboratory, in determining the visibility of the penetrameters, and in making other readings.

BIBLIOGRAPHY

1. A Morrison (to be published in *Non-Destructive Testing*)
2. W. E. Chamberlain, *Radiology* **38,** 383 (1942)
3. G. C. Henny, W. E. Chamberlain, p. 934 in "Medical Physics, Vol. 2," Otto Glasser editor-in-chief (The Year Book Publishers, Inc., Chicago, Ill., 1950)
4. W. R. Dixon, NUCLEONICS **8,** No. 4, 68 (1951).

"I should like to comment on the question whether it is necessary to use the nuclear chain reaction irreversibly. That is to say, whether it is necessary to go through a thermal cycle. Now, in principle, it is not necessary. One could try and do it reversibly, but that principle is so far from any practical realization that I am inclined to be dogmatic on this point and say that for a very long time to come, say 50 years or 100 years, perhaps never, we shall not be able to realize it. I think a considerable amount of thought has been given to this and, so far as I know, nobody has been able to think of any means other than degrading the energy which comes directly from fission into common or garden heat, and then using the heat in orthodox ways."

—M. L. H. Pryce, Fourth World Power Conference, London, July, 1950

Chemical Separation of Fission Products

Useful separation techniques for elements formed in thermal-neutron uranium fission have been developed. Recently declassified methods for elements from Ge to Ce are given

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THE METHODS of chemical separation of radioactive fission products of uranium described in this paper were developed during a survey† of the fission yields of the longer-lived activities produced in the thermal-neutron bombardment of U^{233} and U^{235} (*1*). Although faster and more efficient procedures for separation of some fission products have been developed in recent years, the methods described in this paper are still useful. In this connection, reference should be made to the comprehensive work on fission products in the United States (*2*).

The total mass of radioactive atoms formed in short irradiations is usually less than 10^{-8} of the mass of the target element. Although the chemical separation of these active atoms from the target material is sometimes possible without adding macroscopic amounts of an inactive element of similar chemistry as a carrier, it is often difficult or impossible to do this quantitatively.

For the measurement of the yields of the various radioactive species formed in the fission of uranium, the activities of these species in a uranium target must be determined quantitatively. The same element, or an element having similar chemical properties, is added to a solution of the target as a carrier for the active atoms. The quantity of carrier is usually of the order of a few milligrams, which is large compared to the total amount of radioactive element present.

If the weight of the added carrier is known, quantitative separation of the carrier is unnecessary since an estimate of the total activity originally present in the target solution can be obtained from the fraction of the carrier recovered and counted. This fraction is called the chemical yield. For the procedure to give valid results, however, complete exchange between the active atoms present in a solution and the atoms of the carrier material added is necessary.

When an element has more than one valency state, active atoms of that element may be formed in more than one state; appropriate carriers are therefore added and oxidation-reduction cycles performed to ensure complete exchange. When elements with easily hydrolyzable ions are involved, additional operations must be introduced, e.g., complexing with a suitable agent to ensure that the active and carrier atoms are in states where exchange is possible.

The chemical procedure adopted must give a product that is not contaminated by other radioactive elements. The radioactive purity of the

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† This work was carried out between January 1945 and April 1946 at the Montreal laboratory of the National Research Council of Canada.

product is determined in several ways. The radiation characteristics of the active element studied, i.e., the curves of the decay rate and of the absorption of β- and γ-rays in Al and Pb foils respectively, must not change when additional specific chemical separations are performed on the material. The specific activity of the material (expressed as activity per unit mass, and corrected for decay) must be constant in chemical separations. Finally, chemical separations of suspected contaminating elements should give inactive products. Since quantitative determinations of fission product activities are required, the separated element must be obtained in a stable stoichiometric compound for the estimation of the chemical yield.

When active species of several elements are present in the sample a single chemical separation of a desired element is insufficient, except in a few special cases, to give a radioactively pure product. It is usual to add to the solution carriers for other active elements present in the mixture (these are generally known as "hold-back" carriers). Several chemical separation cycles for the desired element are then made with hold-back carriers added at each stage.

It is sometimes necessary to remove interfering activities before separation of the desired element; this is termed a "scavenging" process. For example, in the separation of Cd and In by precipitation of the sulfides from weakly acid solutions, activities due to other sulfide-group elements are removed by scavenging precipitations of sulfides which precipitate at higher acid concentrations.

The order of addition of reagents is of utmost importance. If the precipitant is present in the solution before the carrier is added, exchange between the radioactive atoms and carrier may be very slow or incomplete. Procedures involving such preformed precipitates should be avoided where possible.

In many precipitation reactions, particularly where gelatinous precipitates are obtained, activities nonisotopic with the carrier element may be carried down; this process, which may be partial or complete, is known as "coprecipitation." For example, coprecipitation of easily hydrolyzed ions such as those of Zr, Nb, Sb, or Sn can occur in solutions weak in acid, or in the absence of suitable complexing ions.

Although it is possible to separate all of the fission elements from a single sample, it is impracticable to do so. Such a procedure requires the simultaneous addition of all carriers and the use of suitable methods to achieve radiochemical exchange before any other chemical operation is performed. It is better to separate from each sample only a single element or a small group of elements such as Sr and Ba, or Rb and Cs.

Experimental Method

The starting materials were samples of natural uranium and U^{233} as the black oxide, which had been bombarded with neutrons in a reactor for 57 days. The samples were dissolved in fuming nitric acid and the volume of the solution adjusted to 250 ml. Aliquots of this solution containing about 2.4 mg/ml of uranium in the case of the natural uranium sample were used in experiments. Since the samples were allowed to decay for some weeks before chemical investigations were started, only the longer-lived fission species were present (*1*, *3*).

Chemical separation procedures were investigated for the elements from Ge to Pr. The separations were accomplished by using between 2 and 10 mg of the element as carrier; Re carrier was

used for Tc. Long-lived radioactive isotopes of Sr, Y, Zr, Nb, Mo, Ru, Sn, Sb, Te, I, Cs, Ba, Ce, and a rare earth now known to be Pm, were found in the samples; short lived Rh, I, La and Pr activities were found as daughter activities of longer-lived parents.

Appropriate carriers for the elements to be separated were added to the fission-product solution. The solution was then boiled and oxidation-reduction cycles performed to facilitate radiochemical exchange. Appropriate hold-back carriers were added before the first chemical separation and at other stages where separations were made. The usual techniques of chemical analysis on the semimicro scale were employed; precipitates were removed by centrifugation in 15-ml centrifuge cones, or in Lusteroid tubes when HF solutions were used.

The final step in the chemical separation of a fission-product element was the precipitation of a convenient stoichiometric compound. The latter was centrifuged and washed with a suitable aqueous wash solution, then with water and finally, repeatedly with acetone. With the aid of a small pipette the precipitate was mixed with acetone and was transferred to a 1-in. square glass microscope cover slide. The samples were dried under an infrared heat lamp, and during drying were adjusted to give a small spot of uniform thickness. The mass of the active precipitate was obtained by weighing the slide on a microbalance before and after mounting the sample. The cover slide was held by Scotch tape on a card cut to fit the shelves below a Geiger-Müller counter. Activities were measured using a bell-type counter with a mica window of thickness 3 mg/cm^2, and filled with 10 cm of argon and 0.5 cm of alcohol vapor; corrections to the observed activities were made for coincidence losses, for variation in counter efficiency, for self-weakening of β-rays in the sample, etc.

The basic chemical separations used are well known and are described in the literature and in standard analytical texts (*4*, *5*, *6*). Procedures satisfactory from the ordinary analytical standpoint often give products of low radiochemical purity. The method of study used was to separate the desired element by a specific chemical procedure. The radiochemical purity of the product at various stages of the separation was examined and residues or filtrates checked for contaminating activities. In this way the effectiveness of various separation methods for the desired element were compared and suitable procedures introduced to remove troublesome contaminating activities. The procedures described in the next section gave samples of satisfactory radiochemical purity from fission-product solutions containing 10^4–10^6 times the activity of the separated product.

Fission-Product Procedures

Four principal methods are used for the chemical separation of the elements from Ge to Ce formed in the thermal-neutron fission of uranium. Distillation methods are used for Ge, As, Se, Ru, Tc, Sn, Sb; solvent-extraction methods are used for Mo, I, and Br; precipitation methods are used for Rb, Sr, Y, Zr, Nb, Rh, Pd, Cd, In, Te, Cs, Ba, La, Ce, and other rare earths; electrochemical separations are used for Ag and Sb.

Germanium, Arsenic, and Selenium

The chemical procedures used were those of Noyes and Bray (Ref. *5*, pp. 37, 62). Hold-back carriers and carriers for Ge, As, and Se in the various valency states were added to the U solution and the solution boiled under

reflux with 40% HBr. The first distillate was collected, hold-back carriers were added, and a redistillation of the Ge, As and Se bromides was made. Selenium was precipitated from the second distillate by reduction with SO_2 or $NH_2OH \cdot HCl$. The As was recovered as sulfide by H_2S precipitation from $>5N$ HCl-HBr solutions or from HF solutions, Ge remaining in the filtrate in both cases. The Ge was recovered as sulfide after removal of HF by fuming with H_2SO_4.

Small amounts of I and Sn contamination were present in the Ge, As, and Se precipitates. These were dissolved in the minimum of HNO_3, I^- carrier added, and AgI precipitated. The solutions were then made $6N$ in HCl; Se was again reduced by $NH_2OH \cdot HCl$ and As and Ge were precipitated as sulfides from $>2N$ HCl.

Inactive samples of Ge, As, and Se were obtained from samples containing over 10^6 disintegrations per minute of gross fission products, with chemical yields of 40–60%. Since no active species were found, the completeness of radiochemical exchange is not known.

Bromine and Iodine

The procedure used was a modification of that given by Dodson and Fowler (*7*). Both I and Br were extracted from the bombarded U in $0.5N$ HNO_3 solution in the absence of hold-back carriers. In the first experiments Br and I carriers were added as $KBrO_3$ and KIO_3 and followed by equivalent quantities of KBr and KI; the liberated halogens were extracted into CCl_4. Recovery of I showed that the specific activity of the samples obtained from the fission-product solution was very variable. This was attributed to the incomplete exchange of the carrier I and the radioactive I from fission; experiments were made to improve the exchange. The active solutions were refluxed with IO_3^- carrier, then I^- was added in stoichiometric proportions and the iodine taken through several oxidation-reduction cycles using $NaNO_2$ as oxidant and SO_2 as reducing agent. This procedure raised the specific activity of the iodine samples and reproducible results were obtained. After the exchange treatment, the halogens were liberated and extracted into CCl_4. The CCl_4 extracts containing free I_2 and Br_2 were treated as follows:

Bromine. The extract was shaken with a few drops of saturated $NaNO_2$ solution and about 2 ml of $0.05N$ HNO_3 (Ref. *5*, p. 190). Bromine was reduced to Br^- and was removed in the aqueous layer; iodine remained in the CCl_4 layer. Potassium iodide carrier, together with a few drops of SO_2 solution, was added to the aqueous layer. This insured reduction of all the iodine before the addition of $NaNO_2$. Iodine was then removed by a CCl_4 extraction and the cycle repeated. Silver bromide was precipitated from the aqueous layer $2N$ in HNO_3 by addition of $AgNO_3$.

Iodine. After removal of Br by $NaNO_2$, the CCl_4 layer was shaken with sulfurous acid and AgI was precipitated from the solution made $2N$ in HNO_3.

Inactive Br samples and radioactively pure I samples were obtained with chemical yields of about 75–80%.

Cesium and Rubidium

The U solution containing 2 mg each of Rb and Cs carrier was scavenged as follows: a sulfide precipitation with Te, Ru, Sn, Sb, and Ag carriers; a hydroxide precipitation with La, Ce, Y, Zr, and Nb carriers; and finally, a carbonate precipitation with Sr and Ba carriers. Two or three such scavenging cycles gave Rb and Cs of the required radioactivity purity. The carbonate filtrate was acidified with HCl.

Cesium. Cesium was separated from boiling $6N$ HCl solution by the silicotungstic-acid procedure (Ref. *6*, p. 897) and precipitated finally by the chloro-

platinate method (Ref. *6*, pp. 869, 870, 895). Two separation cycles were made, radioactively pure Cs being obtained with a chemical yield of over 90%.

Rubidium. After removal of Cs, the Rb remaining was precipitated by the chloroplatinate method; the Pt was removed from the chloroplatinate precipitate by $N_2H_4 \cdot HCl$ (Ref. *6*, p. 895). Cesium carrier was added and the solution evaporated to dryness. To the residue was added 1 ml of a saturated solution of the sodium salt of 5-nitro-6-chlorotoluene-3-sulfonic acid (*8*). The mixture was heated until a clear solution was obtained. After cooling in ice, the insoluble Rb salt of the organic acid was centrifuged; Cs remained in solution. A few drops of a saturated solution of Cs were added to the precipitate and were evaporated to dryness. A further 1 ml of reagent was introduced and the separated Rb complex washed with a saturated solution of the organic complex, a very small quantity of iced water, and acetone. Samples of Rb having an activity of only a few dpm were obtained with chemical yields of about 70%.

Barium and Strontium

The separation of Ba described elsewhere (*9*) is based on methods that utilize the insolubility of Ba and Sr nitrates in fuming nitric acid (*10*) and of $BaCl_2$ in saturated HCl solutions (*11*). The chromate procedure (Ref. *6*, pp. 122, 125) was used for further purification of Ba from Sr.

In later experiments it was found that this procedure gives inadequate separation of Ba when intense activities of Sr are present. The following modified procedure was developed. After addition to the U solution of 2 mg each of Ba and Sr carriers together with hold-back carriers of La, Ce, Y, Zr, Ru, Sb, Te, and Cs, the solution was evaporated to a small volume. The Ba and Sr nitrates were then precipitated by addition of fuming HNO_3 and by cooling the mixture to 0° C. The precipitate was dissolved in a minimum amount of water, hold-back carriers were added and the nitrates were reprecipitated. The nitrates were dissolved in water; 3 mg each of Ru and Sn carriers were then added and precipitated as the sulfides. The H_2S was boiled off and the solution made slightly acid with acetic acid. After addition of 2 ml of 3*N* ammonium acetate the Ba was precipitated by dropwise addition of 3*N* K_2CrO_4 to the boiling solution. The Sr remained in the filtrate after centrifuging.

Barium. The precipitated chromate was boiled with $(NH_4)_2CO_3$ solution* and the $BaCO_3$ residue washed and dissolved in dilute HCl. Strontium hold-back carrier was added and $BaCrO_4$ reprecipitated. This was dissolved in dilute HNO_3, La hold-back carrier added, and the Ba precipitated with fuming HNO_3 or with dilute H_2SO_4.

Strontium. The Sr was precipitated from chromate filtrate with $(NH_4)_2CO_3$. Then the residue was dissolved in dilute HNO_3, Ba carrier added, and $BaCrO_4$ precipitated. The Sr was finally precipitated from the filtrate as either $SrCO_3$ or $SrSO_4$. Radioactively pure samples of Ba and Sr were obtained with chemical yields of 70–80%.

Zirconium and Niobium†

These elements were separated from U solution and from each other by a method based on the work of W. R. Schoeller (Ref. *6*, pp. 331, 1093). Milligram amounts of Zr and Nb car-

* Barium chromate precipitated in presence of even a slight excess of chromate ion causes coprecipitation of Sr so that little separation is possible. It is necessary, therefore, to precipitate $BaCO_3$ at this point.

† A superior procedure for separation of Zr is the precipitation of $BaZrF_6$ by addition of $Ba(NO_3)_2$ to Zr solution 3*N* in HNO_3 and HF (D. N. Hume, Ref. *2*, paper 245). Procedures for separation of Nb by a coprecipitation with MnO_2 from 10*N* HNO_3 and a $CHCl_3$ extraction of the cupferron complex are also described (*2*).

riers (a small quantity of H_2O_2 was found to be necessary to keep the Nb in HCl solution) and hold-back carriers were added to the U solution. Excess HF was added and the solution boiled. Radiochemical exchange was expected to be difficult with species hydrolyzing as readily as Zr and Nb, but it was considered that with a strong complexing agent in solution, exchange would occur more rapidly.

The specific activity of final samples was increased by boiling the fission-product solution and the carriers in HF solution. The fluoride was removed by fuming with H_2SO_4 and the Zr and Nb were then precipitated from boiling 3*N* acid solution by addition of excess $NH_4H_2PO_4$ solution. The solution was boiled for 15 min and centrifuged. The precipitate was washed twice with saturated $NH_4H_2PO_4$ solution, once with water, and was then boiled with NaOH solution to convert the phosphates to hydroxides. Coprecipitated Sb phosphate is dissolved. Since Nb is partially soluble in the alkaline solution, the mixture was saturated with SO_2 and boiled to precipitate the Nb as the hydrated oxide. The centrifuged hydroxides were washed free from phosphate and dissolved in 6*N* HCl with a trace of H_2O_2, if necessary. Yttrium, La, Ce, Ba, Sr, Sn, Te, and Ru carriers were added to the solution in about 3 mg quantities. The phosphates were precipitated as before and were finally dissolved in HF. Rare-earth fluorides were centrifuged from the Zr and Nb solution at this stage.

The fluoride solution was fumed with H_2SO_4, and added to 25 ml of water and cooled in ice to prevent precipitation of $Zr_2(PO_4)_2$. To this was added 2 mg each of Y, La, and Ce, the solution was made 6*N* in HF, and the precipitated rare-earth fluorides were centrifuged.

The solution was evaporated to dryness and fused with 2 gm each of K_2CO_3 and KNO_3. The fused mass was leached with 0.5*N* KOH in the cold. The Nb dissolved completely leaving a residue of ZrO_2.

Niobium purification. As hold-back carrier, 2 mg of Sb was added. The alkaline solution was then saturated with SO_2 and boiled to precipitate Nb as before. The precipitate was centrifuged, washed, and dissolved in dilute HCl with the addition of a trace of H_2O_2, if necessary. To the solution 2 mg of Zr was added and excess H_2O_2 destroyed with $KMnO_4$. The Nb and Zr hydroxides were precipitated in the cold with NH_4OH. The precipitate was fused as above and Nb then leached from the fused mass and precipitated with SO_2. The precipitate was ignited to the pentoxide, Nb_2O_5.

Zirconium purification. The residue of ZrO_2 was dissolved by fusion with $KHSO_4$. The cold melt was dissolved in water, the solution was made 2*N* in H_2SO_4, and Nb carrier solution was introduced. The solution was heated to boiling, tannin reagent was added, and the flocculent orange-red complex of Nb was precipitated with a minimum of NH_4OH. Two such scavenging precipitations were made, after which the Zr was precipitated and ignited to the oxide.

Although the procedure is long and tedious, radioactively pure samples of Zr and Nb were obtained from fission product solutions containing about 10^6 dpm with chemical yields of about 50%.

Molybdenum

The Mo was first removed from the U solution as the sulfide.* Hold-back carriers were added to the solution 6*N* in HCl. This was saturated with H_2S and heated in a pressure bottle for 15 min. The Mo_2S_3 was removed, dissolved in aqua regia, and hold-back carriers for the sulfide group added;

*A more rapid initial precipitation was α-benzoinoxime (Ref. *6*, p. 587; *12*).

molybdenum was then separated by diethyl ether extraction of either the thiocyanate complex or the compound $MoO_2 \cdot 2HCl$ (Ref. *6*, p. 589). To a $4N$ HCl solution a small amount of Zn was added followed by excess $4M$ NH_4CNS. The red Mo complex was extracted with diethyl ether. Alternatively, the Mo solution was made $8N$ in HCl and $MoO_2 \cdot 2HCl$ extracted by diethyl ether; the partition coefficient for this extraction is small and two extractions were made with a volume of ether twice that of the aqueous phase.

In both procedures the ether layer was washed with $8M$ HCl and evaporated; the residue was treated with HNO_3 and $PbMoO_4$ was precipitated by the addition of lead acetate to the solution buffered with ammonium acetate. The precipitate was dissolved in HNO_3 and $PbMoO_4$ reprecipitated. Chemical yields in this procedure were about 60% and satisfactory decontamination was otained.

Ruthenium and Technetium

Ruthenium was distilled as the volatile tetroxide, RuO_4, (Ref. *5*, p. 40) from solutions $3M$ in H_2SO_4 and $0.5M$ in $NaBrO_3$, or from fuming $HClO_4$-H_2SO_4 solutions; hold-back carriers for Te, Ba, Cs, Ce, Zr, Nb, Sn, Sb, and Mo were present. Nitric acid was removed by fuming with H_2SO_4 or by reduction with formic acid or urea, as it was found to interfere with the RuO_4 distillation. After refluxing to achieve exchange,* the yellow distillate was collected in $5N$ NaOH solution from which Ru was precipitated as the metal by addition of Mg after acidification with HCl. Chemical yields were about 90% and separation factors of the order of 10^6 were obtained with two distillations.

The method used for Tc was that given by Goldschmidt and Perlman (*13*). Technetium followed Ru in the $HClO_4$ distillation. On reduction of the Ru-Tc distillate with alcohol, Ru precipitated as hydrous oxide while the Tc remained in solution. The Tc was removed by addition of ReO_4^- carrier and precipitation by addition of nitron reagent. No Tc activities were found in the present work.

Rhodium

After addition of carriers for most of the fission elements, Rh was precipitated from $0.4N$ HCl solution by H_2S. The precipitate was dissolved in aqua regia, and sulfide-group carriers were added. Other sulfide-group contaminants, As, Ge, Se, Te, Sn, Sb, In, Mo, Ru, Tc, and Pd, were then removed. The As, Ge, and Se were removed by distillation with HBr; Se and Te were precipitated with SO_2 or $N_2H_4 \cdot HCl$;† Ru and Tc were removed by distillation with $HClO_4$; Mo was removed by extraction with ether from $6N$ HCl; Pd was precipitated with dimethylglyoxime or $N_2H_4 \cdot HCl$. The Rh was then separated from Sb, Sn, and In by precipitation from $1N$ HCl by H_2S. This precipitate was dissolved in HNO_3 and the Rh precipitated by reduction with Zn. The freshly precipitated Rh was found to dissolve in hot strong H_2SO_4 which allowed a further separation cycle to be made. No Rh species were found among the longer lived fission-product activities. Chemical yields were of the order of 90%.

Palladium

Palladium and carriers for other sulfide-group elements, Sr, Ba, Ce, Cs, etc., were added to the U solution.

* Present knowledge shows that radiochemical exchange of active Ru and carrier in acid solutions is not necessarily complete. A better method of achieving exchange, due to W. H. Hardwick of the National Research Council, Chalk River, Ontario, Canada, employs alkaline oxidizing fusion of Ru carrier and active material, e.g., with KOH and KNO_3.

† In hot $2N$ HCl, only Te and Se are reduced to the element by SO_2. Hydrazine in $1N$ HCl reduces Pd, Te, and Se to the element. The Rh is not reduced, nor is Ru. Formic acid in $1N$ HCl reduces Rh and Pd to element, but not Te.

The Pd was reduced to the metal by boiling in 1*N* HCl solution with N_2H_4·HCl. This was dissolved in strong HNO_3, hold-back carriers for the other sulfide-group elements and the rare earths were added, and the solution was made 2*N* in HNO_3. The Pd was then precipitated by addition of a slight excess of dimethylglyoxime or α-furildioxime (Ref. *6*, p. 723). The complex was washed and dissolved in aqua regia and, after addition of hold-back carriers, the Pd was precipitated twice as the oxime and was reduced to the element by heating with formic acid. Chemical yields were >90%.

Silver

The method used initially was precipitation of the AgCl from HNO_3 solutions. The AgCl was dissolved in NH_4OH, scavenging precipitations of hydroxides were made, and the AgCl was reprecipitated. This procedure gave unreliable separation, particularly from Pd and, furthermore, the chemical yields were low.

An electrolytic method—the first application of electro-chemical separation to the extraction of active fission products—was developed which was rapid (about 30 min) and gave effective purification. Carrier Ag was added to the fission-product solutions in HNO_3 and the solution boiled to insure radiochemical exchange. No hold-back carriers were required. The solution was electrolyzed using Pt electrodes at a potential suitable to give removal of Ag in about 15 min (Ref. *6*, p. 824). The Ag deposit was washed with dilute HNO_3 and water and the electrode then placed in 3*N* NaCN solution. The Ag was redeposited using a clean electrode. This was washed, dissolved in strong HNO_3, and AgCl precipitated for weighing and counting. The chemical yields were almost 100% and radioactively pure samples were obtained from solutions containing over 10^6 disintegrations per minute of gross fission products.

Cadmium and Indium

The U solution, containing Cd and In carriers with 2 mg each of the other sulfide-group elements and Y, La, Ce, Ba, Sr, Zr, Rb, and Cs, was adjusted to 0.5*N* HCl and saturated with H_2S. (Cd and In are not precipitated in 0.5*N* HCl, although if the Cd concentration exceeds ~0.7 mg/ml, precipitation of CdS will occur.) After removal of the sulfide precipitate, the solution was boiled to remove H_2S, and further quantities of As, Ge, Se, Mo, Ru, Rh, Pd, Ag, Sn, Sb, and Te were added and precipitated as before. This step was repeated. Ammonium acetate and acetic acid were added to the filtrate, and In and Cd precipitated by saturating the solution with H_2S. The In and Cd sulfides were dissolved in sufficient cold 1*N* HCl to give a concentration of 0.1 mg/ml of each metal. Carriers for Ru, Sn, Sb, Se, Te, Y, La, Ce, Zr, Ba, Sr, and Cs were added, and the separation of In and Cd as sulfides was repeated. This cycle was continued until the acid sulfide group, the rare and alkaline earths, and alkali-metal carriers were recovered inactive. Three cycles were usually required. The final precipitate was again dissolved in cold 1*N* HCl. Only Cd and In sulfides were found to be soluble under these conditions; small amounts of Sn, Te, etc., that might follow remained undissolved.

The In and Cd were separated by several methods, including the precipitation of $In(OH)_3$ by NH_4OH, the precipitation of In oxalate or ferrocyanide in the presence of excess NH_4OH, or the precipitation of In by K_2CrO_4 from neutral solution.

The best separation was achieved by the precipitation of In basic acetate from dilute acetic acid solution. Cerium, La, Y, Ba, Sr, Zr, Nb, and Cs carriers were added to the acid solution

of In and Cd. This solution was made slightly alkaline with NH_4OH and then faintly acid with HCl. Any precipitate, e.g., of Zr and Nb, formed at this stage was removed. Excess solid Na acetate was added to the solution and the mixture boiled for a few minutes and In basic acetate precipitated. This was centrifuged, washed with water, dissolved in dilute acid, and In reprecipitated.

The Cd was recovered from the filtrate after the removal of In by precipitation with H_2S from 0.2*N* acid solution in the presence of La, Ce, Y, Zr, Ba, Sr, and Cs carriers. The precipitate was dissolved in dilute HCl and the solution boiled to remove H_2S. Rare earths, Zr, Ba, Sr, Cs, and In hold-back carriers were added and Cd reprecipitated either by the addition of an equal volume of 5% aqueous solution of allyliodide-hexamine, or by the addition of an equal volume of phenyltrimethylammonium iodide reagent (2% aqueous solution containing 5% KI). In these two reactions, elements which precipitate as iodides (Ag, Sb, Pd) interfere and must be absent. Chemical yields of Cd and In in the procedures that were used were of the order of 50–60%.

Tin

Tin carrier was added to the U solution and exchange achieved by oxidation-reduction cycles between Sn^{II} and Sn^{IV}. Germanium, As, and Se were then distilled from the 40% HBr solution, Sn remaining in the Sn^{II} state. About 0.2 ml strong H_2SO_4 was added to the residue followed by strong HNO_3 or other oxidizing agent to oxidize Sn^{II} to Sn^{IV} (in which state it is volatile as $SnCl_4$ which boils at 114° C), and Sb^{III} to Sb^{V} ($SbCl_5$ is less volatile in HCl solutions than $SbCl_3$ which boils at 223.5° C). The Sn was then distilled from 12*N* HCl solution (Ref. *5*, p. 70). The distillate was collected, hold-back carriers for Sb and other elements were added, and the procedure repeated. The second distillate was neutralized with NH_4OH, Sb carrier added, and the solution saturated with oxalic acid. Hydrogen sulfide was then passed into the hot oxalic acid solution to precipitate Sb_2S_3; Sn remained in the solution as the complex oxalate.

The oxalate filtrate was boiled to remove H_2S; Sb carrier was added, and the Sb_2S_3 again precipitated. Finally, the oxalate was destroyed by the addition of a slight excess of $KMnO_4$ to the hot solution acidified with H_2SO_4. The solution was treated with Fe to reduce the tin to the Sn^{II} state, and to remove any traces of Sb. The solution was then centrifuged and, after adjusting the acidity to 0.4*N*, SnS was precipitated. Chemical yields of Sn were about 70% with separation factors of about 10^6 when separation cycles were repeated three times. The procedure is very tedious.

Antimony

Formerly antimony was separated from fission-product solutions, after the distillation of Ge, As, Se, and Sn, by reduction to Sb^{III} and distillation from H_3PO_4 solution (to complex Sn) in a stream of HCl gas. The Sb was then precipitated as Sb_2S_3 from oxalic acid solution.

A much faster and neater method using the electrolytic reduction of Sb^{III} to SbH_3 (*14*) was employed. Radiochemical exchange was first assured between Sb^{III}- and Sb^{V}-carrier and active atoms by boiling the strong HCl solution and by oxidation with Br_2 and reduction with $N_2H_4 \cdot HCl$. Antimony sulfide was then precipitated by H_2S from dilute HCl solution. No hold-back carrier should be present because deposition of other metals at the cathode causes lowering of the overvoltage. The sulfide was destroyed by fuming with H_2SO_4 and a few drops

of HNO_3. The solution, diluted to about 4*N* H_2SO_4, was electrolyzed in a closed cell at an applied potential of about 4 volts; a small Pt anode and a large cylindrical cathode of pure Pb were used. A stream of N_2 carried the SbH_3 into 1.5*N* $AgNO_3$ solution. The precipitate of Ag and Ag_3Sb was washed with water and boiled with 6*N* HCl. The Sb was dissolved and, after removing the insoluble residue, the acidity of the solution was adjusted and Sb_2S_3 precipitated.

This procedure gave an 80% yield of Sb carrier when milligram amounts were used. The separation was made in 10–15 min and samples of constant specific activity were obtained from solutions containing over 10^6 disintegrations per minute of fission-product activities. Partial contamination of Sb by As and Se activities might have been expected, but in the present work no long-lived activities of As and Se were present. Any As and Se could have been readily removed by distillation with HBr.

Tellurium

Since no long-lived Se activities were present in the fission-product solutions used, Te was removed from a 2*N* solution of U by SO_2 reduction. Radiochemical exchange between active species and the added TeO_3^{--} and TeO_4^{--} carriers was achieved by boiling the HCl solution. The Te precipitate was dissolved in a small amount of strong HNO_3 and Nb and La carriers were added and precipitated by NaOH. After this scavenging the Te was again reduced from 2*N* HCl solution by SO_2. The cycle was repeated until the specific activity of Te was constant. In the presence of Se activities, Te could be separated by using the precipitation of Se by SO_2 from 12*N* HCl solutions (Ref. 6, pp. 779, 782) in which Te remains in the solution. Chemical yields were about 95%.

Yttrium, Cerium, and Rare Earths

Yttrium, Ce, and other rare earths were precipitated directly from hot solutions 3*N* in HNO_3 by the addition of HF. Hold-back carriers for Zr, Nb, and the sulfide-group elements were present. The washed fluorides were heated to fuming with $HClO_4$;* the solution was diluted; Sr, Ba, and Cs hold-back carriers were added; and the rare-earth hydroxides were precipitated from the boiling solution by NH_4OH. The hydroxides were dissolved in dilute HCl, Zr and Nb carriers added, and the fluorides reprecipitated. These separations were repeated until the residual solutions were inactive. Three cycles were usually adequate.

Cerium. Cerium was separated from Y and other rare earths by precipitation of the tetravalent iodate or phosphate.† The rare-earth hydroxides were dissolved in 2 ml of concentrated HNO_3, and 0.1 gm of powdered $KClO_3$ or $NaBiO_3$ was added and the solution boiled. To the solution, 5 ml of 0.35*M* KIO_3 in 1*N* HNO_3 was then added and the mixture cooled and centrifuged after 10 min. The washed precipitate of $Ce(IO_3)_4$ was metathesized with hot 6*N* KOH solution and the hydroxide centrifuged. Cerium was also separated as $Ce_3(PO_4)_4$ by the addition of $NH_4H_2PO_4$ to the boiling HNO_3 solution. The phosphate was converted to the hydroxide as before. Either procedure was repeated using hold-back carriers. Ceric oxide, CeO_2, was obtained for measurement by ignition of ceric oxalate, which was precipitated from a 3*N* HNO_3 solution of Ce by addition of an equal volume

* A more satisfactory way for removing F^- was by complexing with H_3BO_3. Rare-earth fluorides were dissolved in 3*N* HNO_3 saturated with H_3BO_3, from which solution the hydroxides were precipitated by NH_4OH or NaOH.

† Zr and Th activities formed by uranium decay are removed by precipitation as the iodate or phosphate using Zr carrier; Ce is held in the 3+ state in this step. In the present work negligible activities were found in such a Zr precipitation.

of a saturated solution of oxalic acid. Chemical yields were about 80%.

Yttrium and the rare earths. These remained in the filtrate after removal of Ce. Yttrium was separated from the La group of rare earths by the well-known double sulfate procedure (Ref. *6*, p. 251). Praseodymium was partially separated by the oxidizing fusion method (Ref. *5*, p. 230). In both these cases, poor separation factors were obtained and chemical yields were low.

The well-known ion-exchange methods are now used in the separation of Y and the rare earths; Sm and Eu are usually isolated by procedures that utilize amalgam formation and precipitation of $EuSO_4$, respectively.

Separation of Daughter Activities

To check the possible existence of daughter activities of the radioactive isotopes formed in fission, appropriate chemical separations were made. The only parent-daughter systems in the fission-product solutions studied were

$$Te^{132}(77h) \rightarrow I^{132}(2.3h)$$
$$Ba^{140}(12.8d) \rightarrow La^{140}(40h)$$
$$Sr^{90}(19.9y) \rightarrow Y^{90}(61h)$$
$$Ce^{144}(275d) \rightarrow Pr^{144}(17.5m)$$
$$Zr^{95}(65d) \rightarrow Nb^{95}(35d)$$
$$Ru^{106}(1.0y) \rightarrow Rh^{106}(30s)$$

Chemical separation of elements of charge $Z + 1$ have been made from all the active elements of charge Z studied. The methods used were essentially those given for the separation of fission-product elements from irradiated U solutions. These methods were suitably modified since contamination with only one element, the parent, was possible. The following were typical separations. Yttrium was separated from Sr by precipitation of YF_3; this precipitate was fumed with $HClO_4$ and the YF_3 reprecipitated after addition of Sr hold-back carriers. Antimony was separated from Sn by precipitation of Sb_2S_3 from an oxalic acid solution; after solution of the precipitate in strong HNO_3, Sn hold-back carrier was added and a further reprecipitation of Sb_2S_3 from saturated oxalic acid solution was made.

BIBLIOGRAPHY

1. W. Grummitt, G. Wilkinson, *Nature* **158,** 163 (1946); **161,** 520 (1948); National Research Council of Canada, Report 470 (1951)
2. C. D. Coryell, N. Sugarman, editors, "Radiochemical Studies: The Fission Products" National Nuclear Energy Series, IV-9 (McGraw-Hill Book Co., Inc., New York, 1951)
3. Plutonium Project: Nuclei Formed in Fission, *J. Am. Chem. Soc.* **68,** 2411 (1946); *Revs. Mod. Phys.* **18,** 513 (1946); C. D. Coryell, N. Sugarman, editors, "Radiochemical Studies: The Fission Products" NNES, IV-9, Appendix C—nuclides formed in fission (McGraw-Hill Book Co., Inc., New York, 1951)
4. R. K. McAlpine, B. A. Soule, "Prescott and Johnson's Qualitative Analysis" (D. Van Nostrand Co., Inc., New York, 1932)
5. A. A. Noyes, W. C. Bray, "System of Qualitative Analysis for the Rare Elements" (The Macmillan Co., N. Y., 1927)
6. W. W. Scott, N. H. Furman, "Standard Methods of Chemical Analysis," 5th ed. (D. Van Nostrand Co., Inc., New York, 1939)
7. R. W. Dodson, R. D. Fowler, *Phys. Rev.* **57,** 966 (1940)
8. H. Davies, W. Davies, *J. Chem. Soc.* **123,** 2976 (1923)
9. W. E. Grummitt, J. Guéron, G. Wilkinson, L. Yaffe, *Can. J. Research* **25B,** 357 (1947)
10. C. Lieber, *Naturwissenschaften* **27,** 421 (1939)
11. O. Hahn, F. Strassmann, *Naturwissenschaften* **27,** 11 (1939)
12. H. B. Knowles, *J. Research Natl. Bur. Standards* **9,** 1 (1932)
13. B. L. Goldschmidt, I. Perlman, paper 102 in "Radiochemical Studies: The Fission Products," C. D. Coryell, N. Sugarman, editors, NNES IV-9 (McGraw-Hill Book Co., Inc., New York, 1951)
14. J. Grant, *Analyst* **53,** 626 (1928)

Charts for determining

Optimum Distribution of Counting Times

Total counting time can be minimized by properly choosing background and sample counting times. Graphs are presented for making this choice and finding the total counting time and the distribution of counts for a given statistical error

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WHEN MEASURING the strength of many radioactive samples of only moderate intensity, it is important to minimize the time required to measure each sample. It is then possible to measure more samples per unit time with a particular statistical error, and counting equipment and operating personnel can be used most efficiently. Thus, a given counting load can be handled with a smaller investment in equipment and personnel. Also, under this condition, rapidly decaying samples can be measured with a more favorable statistical error in the short time that is available before the activity is too low.

Except for strong samples, much of the counting time is spent determining the magnitude of the background counting rate. This is necessary so that the statistical error of the background rate will not introduce a large error when the observed counting rate is corrected for background.

If the background is inadequately measured its statistical error will appear as a lack of precision in the final results.

To obtain the desired precision, one might repeat the determination or increase the total counting time. However, up to a certain point, it is more efficient to increase background counting time. Beyond this point the statistical error contributed by the background value is small compared to that contributed by the sample value, and one might more profitably concentrate on the latter to improve the accuracy of the measurement.

An optimum distribution of effort between the counting of background and sample exists, and the usefulness of a quantitative treatment of the relationships connecting these quantities is apparent.

Calculation of Optimum Distribution

The time required to measure a single sample is

$$T = T_b + T_s \qquad (1)$$

where T_b is the time required to measure the background, and T_s is the time required to measure the sample.

Equating to zero the derivative of Eq. 1 with respect to T_b establishes a condition for minimum T

$$\frac{dT}{dT_b} = 1 + \frac{dT_s}{dT_b} = 0 \qquad (2)$$

To evaluate the last term in Eq. 2 it is necessary to have a relationship be-

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tween T_s and T_b. This may be obtained as follows: The corrected counting rate of the sample is

$$C = C_s - C_b \tag{3}$$

where C_s is the counting rate of background and sample combined, and C_b is the background counting rate. The probable statistical error, ϵ_s, associated with C_s is equal to the error in number of counts divided by the counting time, T_s (assuming errors in time measurement to be negligible)

$$\epsilon_s = \frac{0.6745\sqrt{C_s T_s}}{T_s} = 0.6745\sqrt{\frac{C_s}{T_s}} \tag{4}$$

The factor 0.6745 is the coefficient for that error for which there is a 50% probability of its being exceeded. If standard errors are used, a coefficient of unity should be substituted for the factor 0.6745 in this work.

The probable statistical error, ϵ_b, associated with C_b equals the error in number of background counts divided by the counting time, T_b

$$\epsilon_b = 0.6745\sqrt{\frac{C_b}{T_b}} \tag{5}$$

The probable statistical error, ϵ, associated with C in Eq. 3 is

$$\epsilon = \sqrt{\epsilon_s^2 + \epsilon_b^2} = 0.6745\sqrt{\frac{C_s}{T_s} + \frac{C_b}{T_b}} \tag{6}$$

The solution for T_s is

$$T_s = \frac{C_s}{\left(\frac{\epsilon}{0.6745}\right)^2 - \frac{C_b}{T_b}} \tag{7}$$

Differentiation with respect to T_b gives

$$\frac{dT_s}{dT_b} = \frac{-C_s C_b}{T_b^2\left[\left(\frac{\epsilon}{0.6745}\right)^2 - \frac{C_b}{T_b}\right]^2} \tag{8}$$

which, when substituted into Eq. 2, results in

$$\frac{dT}{dT_b} = 1 - \frac{C_s C_b}{T_b^2\left[\left(\frac{\epsilon}{0.6745}\right)^2 - \frac{C_b}{T_b}\right]^2} = 0 \tag{9}$$

The solution for T_b is, then

$$T_b = \frac{C_b \pm \sqrt{C_s C_b}}{(\epsilon/0.6745)^2} = \left(\frac{0.6745}{\epsilon}\right)^2 C_b\left(1 \pm \sqrt{\frac{C_s}{C_b}}\right) \tag{10}$$

To choose the proper sign in Eq. 10 it is necessary to test both of the possible solutions for minimum condition. This is done by substitution into the second derivative of Eq. 1 with respect to T_b, which is best obtained from Eq. 9

$$\frac{d^2T}{dT_b^2} = \frac{2C_s}{\frac{T_b}{C_b}\left[\frac{T_b}{C_b}\left(\frac{\epsilon}{0.6745}\right)^2 - 1\right]^4 C_b^4} \tag{11}$$

Substitution of Eq. 10 into Eq. 11 gives for the second derivative

$$\frac{d^2T}{dT_b^2} = \frac{2C_s}{\left(\frac{0.6745}{\epsilon}\right)^2\left(1 \pm \sqrt{\frac{C_s}{C_b}}\right)} \times \frac{1}{\left[\left(1 \pm \sqrt{\frac{C_s}{C_b}}\right) - 1\right]^4 C_b^4} \tag{12}$$

or

$$\frac{d^2T}{dT_b^2} = \frac{2}{\left(\frac{0.6745}{\epsilon}\right)^2\left(1 \pm \sqrt{\frac{C_s}{C_b}}\right) C_s C_b^2} \tag{13}$$

Since $C_s = C_b + C$, C_b is always smaller than C_s. Consequently, the radical in the denominator of Eq. 13 is larger than unity, making the whole expression negative if the negative sign is chosen. If, however the positive sign is chosen, Eq. 13 is positive for all positive values of C_s, C_b, and ϵ. Thus the condition for minimum T is expressed by Eq. 10 using the positive sign on the radical

$$T_b = \left(\frac{0.6745}{\epsilon}\right)^2 C_b\left(1 + \sqrt{\frac{C_s}{C_b}}\right) \tag{14}$$

The quantity ϵ is the absolute probable statistical error of the corrected counting rate. It would be more useful to have the expression in terms of E, the percentage probable statistical error which is written in the form

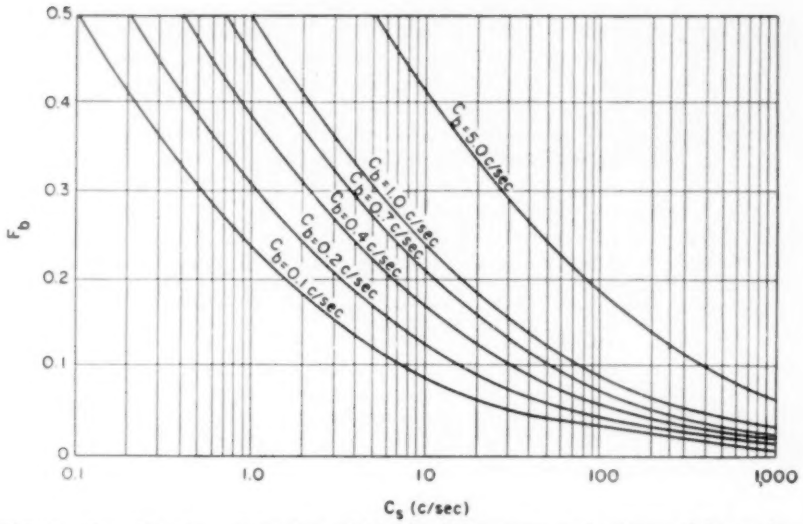

FIG. 1. Fraction of counting time which should be spent on background for various background and sample-plus-background counting rates

$$E = 100\epsilon/C = 100\epsilon/(C_s - C_b) \quad (15)$$

Substituting this into Eq. 14 gives

$$T_b = \left(\frac{67.45}{E}\right)^2 \frac{C_b(1 + \sqrt{C_s/C_b})}{(C_s - C_b)^2} \quad (16)$$

Equation 16 is an expression for the time that should be devoted to measuring background counting rate to minimize total counting time. Substituting Eqs. 15 and 16 into Eq. 7 yields

$$T_s = \left(\frac{67.45}{E}\right)^2 \frac{C_s(1 + \sqrt{C_b/C_s})}{(C_s - C_b)^2} \quad (17)$$

Equation 17 is an expression for the time that should be used for the measurement of the sample and background combined.

The fraction of counting time which should be devoted to measurement of background is the ratio of T_b to $T_s + T_b$. Substituting Eqs. 16 and 17, this ratio is found to be

$$F_b = \frac{1}{1 + \sqrt{C_s/C_b}} \quad (18)$$

Many modern counting laboratories measure a sample until a preset number of counts has been accumulated. The optimum numbers of counts which should be accumulated for minimum total counting time are

$$N_b = T_b C_b = \left(\frac{67.45}{E}\right)^2 \frac{C_b^2(1 + \sqrt{C_s/C_b})}{(C_s - C_b)^2} \quad (19)$$

$$N_s = T_s C_s = \left(\frac{67.45}{E}\right)^2 \frac{C_s^2(1 + \sqrt{C_b/C_s})}{(C_s - C_b)^2} \quad (20)$$

where N_b is the number of background counts and N_s is the number of counts of sample and background combined for minimum total counting time.

Equation 18 was used to prepare Fig. 1 which shows the fraction of the total counting time which should be spent measuring the background as a function of C_b, the background counting rate, and of C_s, the counting rate of sample and background combined.

Equations 19 and 20 were used to prepare Fig. 2 which shows the best distribution of counting effort in terms of number of counts, as a function of

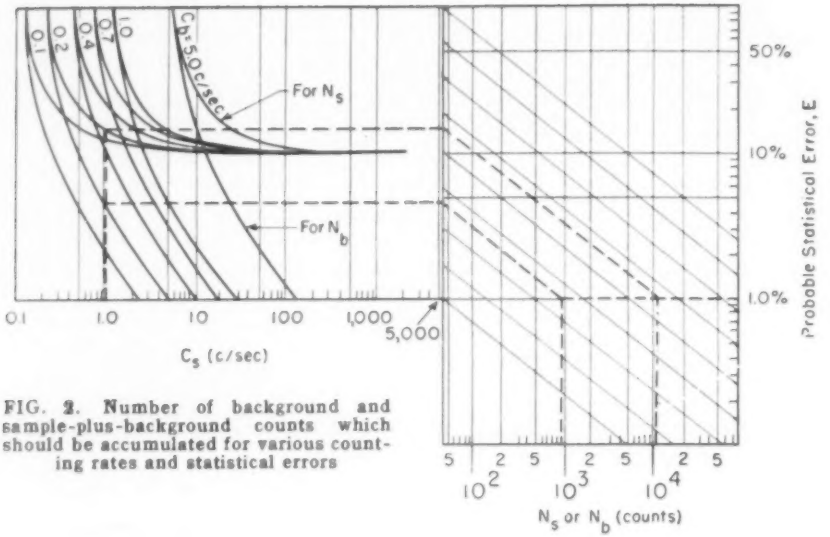

FIG. 2. Number of background and sample-plus-background counts which should be accumulated for various counting rates and statistical errors

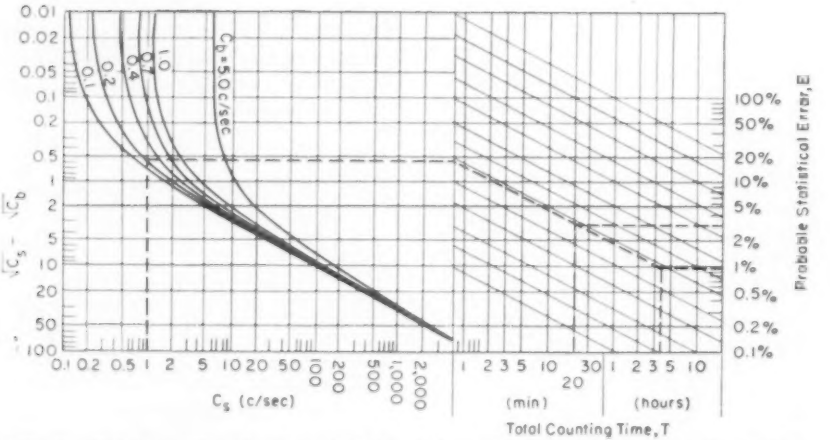

FIG. 3. Total counting time required to attain various statistical errors for various counting rates if optimum distribution is used

C_b and C_s and for various probable statistical errors.

To illustrate the use of Fig. 2, consider a sample having a counting rate of 1.0 c/sec in the presence of a background of 0.2 c/sec. Find the value 1.0 c/sec on the horizontal scale labeled "C_s." Move upward along the grid lines until the 0.2 line of the set of curves labeled "N_b" is reached. Move horizontally until the vertical line dividing Fig. 2 into two parts is reached. Move down diagonally, parallel to the slanting grid lines, until the level of the desired probable error is reached as indicated on the right hand vertical

scale, say 1% in this case. Move down to the horizontal scale labeled "number of counts" and read $N_b = 900$, the optimum number of background counts for minimum total counting time. The same procedure is followed for obtaining the optimum value of N_s, except that in this case the set of curves labeled "N_s" is used.

Figures 1 and 2 illustrate the obvious fact that where counting rates are large compared to the background rates, the latter may be ignored except for spot checks.

For very weak samples the counting time should be distributed approximately equally between background and sample, as evidenced by the convergence of corresponding lines for background and for sample at low values of C_s in Fig. 2.

The graphs are most useful in the intermediate range where the best distribution of effort is not intuitively apparent.

Total Counting Time

It is often desirable to know just how low the statistical error can be made in a limited counting time. Having this information, one can quickly decide whether any particular measurement is feasible and can arrange the experiment to produce samples that have sufficient intensity.

The total time required for counting both background and sample may be obtained by substituting Eqs. 16 and 17 into Eq. 1

$$T = \left(\frac{67.45}{E}\right)^2 \left[\frac{\sqrt{C_b} + \sqrt{C_s}}{C_b - C_s}\right]^2$$

$$= \left(\frac{67.45}{E}\right)^2 \left(\frac{1}{\sqrt{C_s} - \sqrt{C_b}}\right)^2 \quad (21)$$

$$\log T = 2 \log 67.45 - 2 \log E - 2 \log (\sqrt{C_s} - \sqrt{C_b}) \quad (22)$$

Equation 22 was used to prepare Fig. 3 which shows the total counting time, T, required to reduce the probable statistical error to any desired value, E, for any background counting rate, C_b, and for any sample-plus-background counting rate, C_s. Figure 3 applies only to the minimized total counting time that has been obtained with the aid of Fig. 1 or 2.

Suppose that it is desired to know how long it will take to measure, with 1% probable statistical error, the counting rate of a sample having approximately 1 c/sec in the presence of a background of approximately 0.2 c/sec. Find the value 1 c/sec on the horizontal scale "C_s" in Fig. 3. Move directly up along the grid lines until the line corresponding to $C_b = 0.2$ c/sec is encountered. Move horizontally along the grid lines until the vertical line dividing Fig. 3 into two parts is encountered. Move down diagonally, parallel to the slanting grid lines, until the level of $E = 1\%$ is reached. Read off the total required counting time, 4 hours, on the horizontal scale "T." The dashed lines indicate the steps outlined.

If four hours are not available for counting, one may decide to be content with a higher statistical error. For example, if a total of only 20 min is available for counting, then the probable statistical error will be 3%, as shown by the dashed line. Other alternatives are to prepare a more intense sample, to reduce the background counting rate, or to abandon the experiment.

Figure 3 can be used to evaluate the advantage which might be obtained by reducing the background. If, for example, in the illustration above, the background had been 1.0 instead of 0.2 c/sec, C_s would have been approximately 2.0 c/sec, and the required total counting time for 1% statistical error would have been approximately 8 instead of 4 hours for each measurement of the sample. —END

Detection of Scrapers in Pipe Lines

Scraping devices stuck in underground pipe lines can be located with a G-M counter if radioactive sources are attached to them. Method will work with five feet of dirt over pipe

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A PIG OR GO-DEVIL that is stuck in a pipe line for oil or gas can be located by the use of radioactivity. Both of these devices are essentially scrapers. A pig consists of a pair of heavy rubber washers mounted one behind the other on a spacer bar. The diameter of the washers is slightly larger than the inside of the pipe, thus assuring a tight fit. A go-devil is a pig with two sets of spring-mounted spurs and a set of spring-mounted scraper vanes added. The spurs ride against the pipe to break up obstructions on the pipe wall; the vanes are curved to fit the pipe.

These scrapers are pushed through newly constructed pipe lines with compressed air to demonstrate that the line is completely free of obstructions such as weld icicles. When an oil line is in operation, a scraper is sent through with the oil at regular intervals to remove the wax that forms on the inside of the pipe.

Sometimes the scrapers get stuck. This occurs more often with newly laid, unused pipe, and is more frequent with smaller diameter pipes. In the case of the larger pipes—10 to 20 in. diameter—a hold-up is uncommon because of the large force involved. But a leak past the rubber washers may decrease the pressure enough that a small obstruction can stop the scraper. Such a leak can be caused by a longitudinal seam that depresses the rubbers.

Locating a stuck scraper to release it can be both time consuming and expensive. A study has been made of the possibility of dealing with this problem by means of a radioactive source attached to the scraper. The scraper could then be located with a counter.

Preliminary Tests

A Co^{60} source with a strength of 85 mg radium equivalent was obtained from the National Research Council of Canada, Ottawa, Ontario, Canada. Rough experiments indicated that such a source, enclosed in a pipe, would be detectable under four feet of dirt if a portable counter with a 30 mg/cm² beta-gamma G-M tube were used (Tracerlab TGC-5).

It was desirable to know the coefficient of absorption of dirt for the gamma radiation from Co^{60}. A figure was obtained by digging four post holes four feet apart in normally compacted soil. The Geiger tube was placed in one hole and the source successively in each of the others, and counting rates were measured. When corrected for inverse square law, counter dead time and background, the results gave a good straight line. The absorption coefficient was calculated as 0.16 per inch, giving a half-value thickness of 4.4 in. This value would vary somewhat for different soils, and it would vary a good deal for different degrees

of packing. It was clear that a variation of a few inches in soil covering a pipe would greatly affect the possibility of detecting a scraper.

For attaching the source to the scraper, the following method was used. An ordinary 2-in. pipe cap was brazed onto the back of the scraper. Into this was screwed an aluminum cylinder with ¼-in. walls. The source was placed in this cylinder, and the open end was then closed with a second cap. The aluminum container and the steel wall of a pipe line (¼-in. thick) together reduce the radiation to 70% of that from the bare source.

Pipe-Line Tests

A test was arranged in cooperation with a pipe-line construction company operating in the Canadian province of Alberta. The pipe was 8 in. in diameter and the soil cover was 52 in. thick. The scraper was stopped on three separate occasions by removing the driving pressure. On each occasion it was successfully located. However, the counting rate directly over the source was only about twice background.

Since this demonstration, the method has been used on several occasions. On one of these there were two pipe lines, a 10 in. and a 3 in., both 12,000 ft long. The normal cover was 42 in. It was necessary to locate the scraper once in the 10-in. pipe and several times in the 3-in. pipe. In some spots along the pipe line there was a back-fill ridge one to three feet above level ground. The scraper stopped in one of these places on one occasion, and a complete search of the line failed to detect it until the ridge was moved by a bulldozer.

Where the back-fill was level with the surrounding ground, the Geiger-tube response was very pronounced. The count began to increase over background approximately four feet from the spot where the source was finally located. At the position of maximum response the count was many times background.

Extension of Method

Since the field tests of the method were successful, the possibility of using larger sources to extend the method to thicker soil cover was investigated. The half-value thickness of 4.4 in. was obtained for compacted clay. For the fill covering a pipe line the figure would vary above this value. Nevertheless an increase of overburden of a few inches may effectively hide the source if one is working close to the detection limit.

For example, detection of an 85-mg-radium-equivalent source through 52 in. of cover was successful, but it was on the borderline. The counter had to be held close to the ground and progress was necessarily slow. Where the cover was 60 in. no detectable response was obtained. But with a fairly uniform cover of 42 in. fairly rapid progress could be made since the peak response at ground level was at least ten times background.

To estimate the value of the method for greater depths of cover, the following approximations were made:

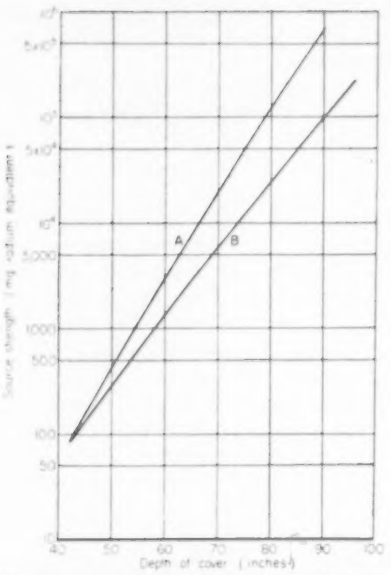
1. Using a 30-mg/cm²-wall tube at ground level, ideal response is obtained with a source of 85 mg radium equivalent and a cover of 42 in.

2. The half-value thickness for compact dirt is 4.4 in.; for loose dirt, 6.0 in. (These two figures probably provide lower and upper limits for the dirt in a pipe-line ditch.)

3. The source is held in an aluminum container ¼-in. thick that is inside a 3-in. steel pipe ¼ in. thick.

Based on these assumptions, the illustration on the next page shows the source strengths needed for various cover thicknesses. A curve is shown for each assumed half-value thickness.

The 6.0-in. value is probably too high for loose dirt. No experiments



Source strength required for detection at various cover distances, as plotted for two half-value thicknesses: *A*, 4.4 in.; *B*, 6.0 in.

have been performed on this in this study. It is probable that curve *B* in the figure gives absolute minimum values in terms of the assumed ideal source strength at 42-in. cover.

The source strength assumed as necessary with 42-in. cover might be reduced somewhat, thus reducing required source strength for all thicknesses of cover by the same factor, but this would reduce the speed at which the line could be surveyed. It appears that a source slightly greater than 1 gm radium equivalent would be needed for a 5-ft cover. The problem of personnel hazard would become important with a source of this size and might be the limiting factor.

However, normal cover is 3½ ft. At depths much in excess of this it is probably better to locate the source by elimination of the shallower places first and then by dealing with the deeper places as special problems. Covers of 8 ft are sometimes encountered, but only at road and river crossings. A back-fill ridge can, of course, be removed with a bulldozer.

A G-M counter was used in these experiments. If a scintillation counter were used as the detecting element, the increased sensitivity might make it unnecessary to remove back-fill ridges in most circumstances.

Safety of Personnel

The major personnel hazard would occur if the scraper stopped. Each time a stoppage occurs it is necessary to dig down to the pipe, thus exposing workmen to the radiation. It is not valuable to have a source sufficiently strong to be detected if at the same time it is too strong to allow men to work for a short time near the bare pipe. A study of the personnel hazard was therefore carried out.

As of July, 1950, the recommended tolerances (*1*) for the absorption of gamma radiation from a source of energy less than 3 Mev are:

For whole-body radiation: The maximum permissible dose received by the surface of the body shall be 0.5 r per week. This rate corresponds to 0.3 r per week measured in free air.

For partial exposure: The maximum permissible dose confined to a particular organ or tissue should not exceed the permissible dose for whole-body irradiation, except for hands and forearms. In this case the maximum permissible dose is 1.5 r per week at a depth corresponding to 7 mg/cm². This corresponds to approximately 0.9 r per week measured in free air.

In the course of handling the source the hands and forearms will receive a larger dose than the rest of the body. If it is necessary to dig down to the pipe, the feet and legs will be more exposed. In either case one might feel safe in using the 0.9 r per week figure as the permissible dose rate. Nevertheless,

Cover (in.)	*Value of S (from graph) (mg Ra equiv.)*	*Value of T (from equation) (min)*	*Thickness of lead storage container (2) (cm)*	*Weight of container (lb)*
42	100	60	3.5	20
60	1,000	6	7	80
72	10,000	0.6	11	230

to be on the safe side, the 0.3 r per week figure will be used. Assuming a 40-hr work week, this gives a maximum permissible daily dose of 60 mr.

It has been found that 1 mg radium equivalent of Co^{60} produces approximately 0.73 mr/hr at one meter (*2*). Using this figure with that for the daily permissible dose, one obtains the equation

$$T = 7.6D^2/S$$

where T = time in hours to acquire the daily dose, D = distance from source in feet, and S = Co^{60} source strength in mg radium equivalent.

Using this equation in conjunction with values from the source strength vs cover thickness curve, three exploratory problems have been worked out. In each case it has been assumed that: (1) the major hazard to personnel occurs when the scraper stops and it becomes necessary to expose the pipe; (2) the radiation intensity through the source holder and pipe is 70% of that from the bare source; (3) the minimum working distance from the source is 3 ft. The results of the computations are shown in the table on this page.

The 42-in. cover presents no real difficulty. The working time of 60 min is sufficient if there are several workmen who operate in shifts. The 20-lb storage container is easily carried.

The 60-in. cover is a little more difficult. Whether the method is feasible for this cover would depend chiefly on the number of men available since the 6-min working time per man is short. The 80-lb container, while unhandy, is not a serious limiting factor.

The 72-in. cover would pose extremely difficult if not impossible problems. The half-minute working time per man is prohibitive. The 230-lb container would be quite troublesome to move under field conditions.

Thus, considering present recommended tolerances as well as detection sensitivity of a G-M counter and the absorption of gamma radiation in soil, it would appear that the method will work for soil covers of less than 5 ft.

BIBLIOGRAPHY

1. International Commission Recommendations. NUCLEONICS **8**, No. 1, 28; *ibid*, No. 2, 70 (1951)
2. K. J. Parry, *Atomics* **1**, No. 11, 159 (1950)

Thirty Years Ago

"Leading men of science in Britain, the United States and even Russia are today all corresponding over the question of minute advances in their several laboratories on the structure and behavior of the atom. They believe that they are on the edge of discoveries that may largely, in the sequel, end the struggle for life—at least as far as light and power are concerned."

—*Lord Rutherford, as reported in the* Daily Mail, *in a lecture delivered in 1921 at the Royal Institution*

An Automatic Low-Rate Alpha Counter*

Designed for counting samples obtained with continuous dust recorders, this scintillation counter has an instrument background of 0.107 cph and a geometry of almost 23%. The instrument can be converted for biological-sample counting; it then has a background of 0.39 cph and a geometry of 35.2%

By LEONARD BAURMASH and J. E. DIETRICH

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SAMPLES OF NORMAL atmospheric dust collected with a continuous recorder (*1*) are necessarily of low alpha activity. To obtain a statistically reliable measurement of this activity in a convenient length of time, an alpha counter with a low background is desirable.

A previous article (*2*) described a low-rate alpha counter that used a 1P21 photomultiplier. That instrument had an average background of about 2 cph when used with an aluminum shield which exposed a photosensitive area equal to only $\frac{1}{8}$ in^2.

In the counter described here, the background is reduced and the counter is automatic when used with the sample disk from a continuous dust recorder. After a predetermined counting time has elapsed, the count is recorded on a tape and a new area of the sample disk is placed in position for scanning. The counter can also be adapted for counting samples in stainless-steel counting cups.

The complete unit is shown in Fig. 1. It has no scaling stages but feeds the pulses to a recording register capable of receiving 20 pulses per second. The register has sufficient recovery time to accumulate the counts detected from the low-activity samples.

A cross section of the light-tight enclosure containing the photomultiplier, phosphor, and the sample holder is shown in Fig. 2. The photomultiplier is shielded by a brass tube which holds the aluminum shield and the phosphor screen at the correct distance from the photosensitive surface of the tube.

The shield consists of a thin aluminum sheet with a section cut out to expose $\frac{1}{24}$ of the circular dust-collector disk.

The scintillating screen consists of a piece of transparent Scotch tape placed over the shield opening with the adhesive side down and with a very thin layer of Patterson No. 1101 ZnS(Ag) phosphor on the adhesive surface. The screen scintillates upon bombardment by alpha particles. While type B ZnS-CdS was originally used, the new silver-activated ZnS phosphor has been reported to have twice the light output (*3*).

The sample holder consists of a circular brass plate on which the sample disk is placed. This plate is rotated by means of a solenoid and ratchet arrangement. The solenoid is actuated by an impulse from the cycle timer which also controls the counting time.

* This article is based on work performed under contract AT-04-1-GEN-12 between the U. S. Atomic Energy Commission and the University of California at Los Angeles.

When the counting cycle is completed, the brass plate is rotated 1/24 of a revolution to expose a new section of the dust deposit for counting.

Electric Equipment

A block diagram of the components is given in Fig. 3. All signal circuits are well shielded from microphonic and electrical noise, and the B^+ to each signal amplifier is decoupled. All capacitors and resistors in the high-voltage supply are well insulated from ground. All coaxial fittings are of the low loss type.

Photomultiplier tube and high-voltage power supply. The RCA C-7151 photomultiplier is mounted vertically over the sample disk in the scintillation head. A high-voltage resistor network for supplying the anode voltages is mounted directly on the tube base, and the signal coupling capacitor is connected directly to the anode pin on the tube base by means of as short a connection as possible. High voltage is supplied by means of a coaxial cable, and the signal is transmitted to the main chassis and amplifier chassis through another coaxial cable.

The high-voltage supply is electronically regulated and is variable from 500 to 1,500 volts by means of a potentiometer. A 3C24 transmitting tube is used as a series control tube, and a 6SJ7 tube acts as the shunt tube. It is possible to change the a-c supply from 85 to 120 volts without an appreciable change in the output voltage.

Signal amplifiers. Two 6J6 grounded-grid amplifiers are used to amplify the pulse from the photomultiplier tube. These particular amplifiers, which have been used successfully at this laboratory in practically the same manner, have given very good service. To reduce microphonic noise, the amplifiers are mounted on a separate chassis which in turn is mounted on the main chassis by means of rubber shock mounts. Since this chassis completely shields the amplifiers, practically no electrical noise is induced in the amplifier circuits, and microphonic noise is practically eliminated.

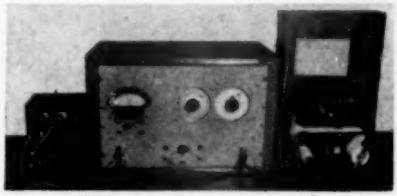


FIG. 1. Complete unit.

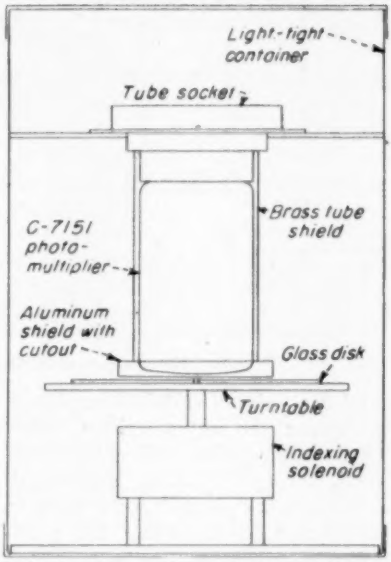


FIG. 2. Cross section of photomultiplier and sample holder

Pulse-forming circuit. This circuit consists of a one-shot multivibrator using an RCA 5964 tube. The output pulse of this circuit is of constant amplitude with a duration of about ½ μsec. The output signal was kept to a low level to eliminate any possible kickback to the amplifiers which could cause double pulsing.

Pulse-shaper circuit. A 6SN7 tube is used in another one-shot multivibrator circuit with time constants that will

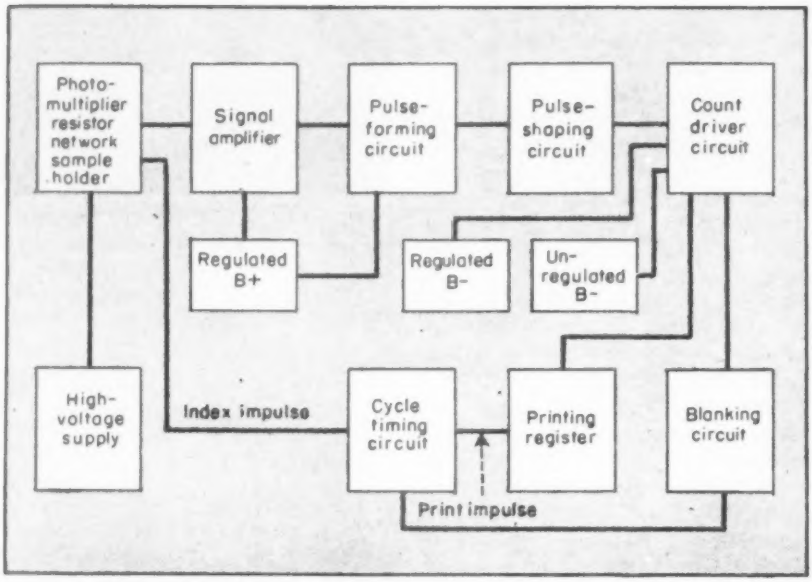


FIG. 3. Block diagram of electric circuits of low-rate counter

develop a pulse of sufficient amplitude to trigger the count-register driver tube into operation and of sufficient length to keep it operating long enough to actuate the count-register relay in the Streeter Amet printer. The pulse-shaper output is a square wave of high amplitude of approximately 100-μsec duration.

Count-register driver circuit. This circuit is a normal power-output stage with the count-register relay of the Streeter Amet printer in series with the B^+ to the plate of the 6AQ5 tube. The stage is biased well beyond cut-off by the -75 volt supply.

Power supplies. The B^+ power supply furnishes regulated 150 volts to the amplifiers, pulse forming circuits, and also to the cathode of the shunt tube in the high-voltage supply. A regulated -75 volt bias is obtained by means of a resistor from the center tap of the power transformer to ground. Regulation is by two OD3 and one OA3 tubes.

Unregulated B^+ is supplied to the count-register driver circuit. The regulated -75 volts is applied to the grid of the count-register driver tube. This prevents spurious signals from triggering the circuit into operation.

Timing circuits. The timing circuits consist of two time clocks. The first clock can be preset to operate for any length of time from 1 to 60 hours, and the second clock will operate for any increment of time between 1 and 20 seconds, depending on the setting. When the preset time has elapsed, the first clock triggers the second clock into operation. While the second clock is in operation, 110 volts a-c is applied to the sample-changing solenoid and to the relay which closes the print circuit.

The time set on the second clock is sufficient for the Streeter Amet printer to stamp out the number of registered counts and reset to zero, and for the sample changing mechanism to place a new sample under the photomultiplier. When the time set on the second clock has elapsed, the hour clock, which has

reset itself, goes back into operation, and a new run begins.

Blanking circuits. A blanking circuit that prevents any counts from being registered during the sample changing period, works in conjunction with, and is actuated by, the time clocks. It consists of two relays with their contacts connected in series with the cathode circuit of the count-register driver tube. The first relay is operated by the hour time clock and remains activated until this clock goes back into operation. The first relay applies direct current to the solenoid of the second relay which will remain activated for a fraction of a second longer than the first relay. This delay in release is achieved by means of a capacitor to ground from one side of the solenoid. This circuit was found necessary because the large transient pulses set up by the activation of the print circuit caused spurious counts.

Print circuit. The print circuit is operated by means of a relay which is closed by the action of the hour clock at the end of its preset cycle.

Index circuit. The sample indexing mechanism consists of a solenoid and a ratchet. The solenoid is energized while the second clock is in operation.

Performance

The complete automatic counter has been in continuous use, 24 hours a day, for three months with no shut down time due to circuit failures.

Preliminary runs on several C-7151 photomultipliers using a Patterson type B ZnS-CdS phosphor gave very satisfactory plateaus of at least 100 volts with an operating voltage of 900 volts. With the new Patterson No. 1101 ZnS(Ag) phosphor, the operating voltage was reduced to 800 volts. During the three-month period, the average background for one tube was 0.107 cph with values ranging from 0 to 0.120 cph for any given eight-hour background count. A second tube had a background of 0.143 cph.

To determine whether the instrument background followed the normal Poisson distribution, 64 hourly counts were recorded by setting the cycle timer to one hour. The results showed 53 hours during which no counts were recorded, 8 hours during which 1 count was recorded, and 1 hour during which 2 counts were recorded.

A polonium standard was prepared by evaporating a thin film of polonium nitrate on a glass disk. This film covered an area equivalent to the opening in the front aluminum shield and was calculated to yield 189 disintegrations per minute. The average geometry of the instrument during the three-month operating time was 22.5 $\pm$ 0.3%.

Counting of Standard Samples

The very low background obtained with the automatic counter seemed to indicate that the circuit and tube could be adapted to counting regularly prepared biological samples. To test this, a 1½-in. diameter screen was prepared with the silver-activated zinc sulfide. A plateau check for this screen also yielded a 100-volt plateau with an operating voltage of 800 volts. At this voltage setting, the geometry of the system was approximately 35.2%.

A background check was made, and 7 counts were recorded in 18 hours, or an average of 0.39 cph. A 5819 photomultiplier was tested with the same diameter and type of screen. This tube system gave a background of 2.01 counts per hour, or roughly five times that of the C-7151 tube.

BIBLIOGRAPHY

1. L. Baurmash, L. Curtis, F. A. Bryan, B. Cassen. Development of a continuous jet impaction method for determining airborne contaminants, UCLA-13 (1949)
2. B. Cassen, C. W. Reed, L. Curtis, L. Baurmash. Low-rate alpha scintillation counter, NUCLEONICS **5**, No. 4, 55 (1949)
3. W. H. Jordan, P. R. Bell. Scintillation counters, NUCLEONICS **5**, No. 4, 30 (1949)

CROSS SECTIONS

*A Low-Energy Gamma-Ray Source for Radiography and Thickness Measurement**

By R. West

Isotope Division, Atomic Energy Research Establishment
Harwell, England

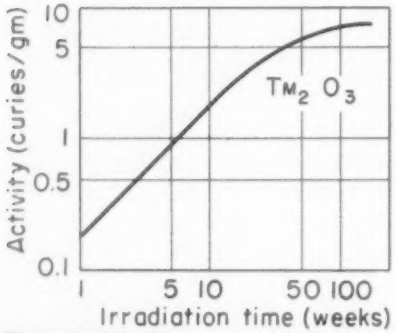
Since the introduction of radioisotopes into the fields of radiography and thickness measurement, a serious gap has existed in the range of suitable sources of low-energy gamma rays. Many possible isotopes have been eliminated because of short half-life, low yield, the unavoidable co-production of unwanted radiations, or other disadvantages.

As a low-energy gamma-ray source, thulium-170 has been found to possess a number of suitable characteristics which do not appear to be offset by disadvantages. Details of this isotope are considered here in the light of some preliminary investigations.

The data given in the table on this page have been reported with sufficient agreement for the purposes of this consideration. The theoretical irradiation build-up curve of Tm^{170} is given in the illustration.

Characteristics of Tm^{170}

Half-life	127 days
Radiations	
Gamma	85 kev (10%)
Beta	890 kev (10%)
	970 kev (90%)
Excitation cross section for target element	105 barns
Thermal-neutron absorption for target element	0.46 cm^2/gm
Production process	$Tm^{169}(n,\gamma)Tm^{170}$
Isotopic abundance of Tm^{169}	100%



Theoretical build-up curve of Tm^{170} for flux of 8×10^{11} neutrons/cm^2/sec (maximum present Harwell pile flux for quantity irradiations)

Source considerations. Thulium is a rare earth of the lanthanide series. The free element is not known to have been isolated. A very limited number of thulium compounds are available, of which Tm_2O_3 was chosen as most suitable for tests. Two high grades of the oxide are available in the United Kingdom: 99.9% purity at £233 per gram and 99.0% purity at £98 per gram. This very high cost of material is offset by virtually infinite source life with

* From a paper presented at the Isotope Techniques Conference, Oxford, England, July, 1951, sponsored by the Atomic Energy Research Establishment, Harwell England.

periodic re-irradiation in the pile. The 99.0% is being used for investigations, and is found to be essentially free of spurious radiations from impurities.

For radiographic purposes, where the best possible source concentration is required, self-shielding of neutrons within the source can possibly be a serious yield-reducing factor during pile irradiation of the source. To investigate this, it is proposed to prepare sources in the form of small flat disks by pressing and sintering the oxide. The disks will be irradiated both together and separately, and the relative yields determined. From this, a compromise between source complication and efficient activation may be decided.

For thickness measurement purposes, source size requirements are not usually stringent, and a layer of the oxide powder may be attached to a flat dish and covered with a thin aluminum sheet. By this means quite strong sources may be prepared efficiently.

An experimental radiograph. Using a crude source, an exposure was made of an aluminum alloy casting ½-in. thick. The 4 × 4 mm source was made up of 90 mg of loose Tm_2O_3 powder in the base of a silica tube, as irradiated. The source strength was approximately 140 mc, effectively 14 mc because only 10% of the disintegrations produce gamma rays.

The casting was exposed for 24 hours at a range of 7 in. on Ilford Industrial B film. The resulting picture shows porosity with good clarity.

Considering the unfavorable combination of distance and source size used for the trial, the results would appear to indicate a fairly sharp gamma spectrum, and promise a considerable improvement with greater source range or smaller source size.

Longer exposures are now being carried out with the same source at a greater distance, and further experimental sources are being prepared.

* * *

The author is indebted to Mr. R. T. P. Derbyshire of the Diffraction Division of the Atomic Energy Research Establishment for making the experimental radiograph, and wishes to thank the Director of AERE for permission to publish this note.

Filtration and Mounting Device for Ca^{45} Measurement

By B. B. Migicovsky and W. A. Evans

Division of Chemistry, Science Service, Department of Agriculture
Ottawa, Ontario, Canada

A filtration device and mounting technique has been developed in this laboratory that is satisfactory for measuring Ca^{45} as the oxalate. The reproducibility is quite good, the coefficient of variability of duplicate measurements being 2%. The apparatus, shown in Figs. 1 and 2, is made of stainless steel. The paper disk on which the precipitate is deposited is No. 50 Whatman; in the preparation of a sample, it is backed by No. 41H Whatman. The diameter of the paper and celluloid (0.04 in. thick) disks is 28 mm. The diameter of paper covered by precipitate is 20 mm, i.e., an area of 3.14 cm^2, thus leaving a rim 4 mm wide for handling the disk.

Procedure. The washed precipitate is deposited with the aid of suction. The suction is removed, the paper with precipitate lifted off, the celluloid disk placed on the platform, suction applied, and the paper disk sucked onto the surface of the celluloid. The edge of the

paper is moistened with acetone by means of a stirring rod or narrow spatula. This fastens the paper to the celluloid and results in a flat, rigid preparation.

After the sample is counted, the quantity of calcium oxalate on the disk is determined by washing the precipitate into a beaker with a stream of water from a wash bottle. The pad is lightly scraped with a spatula, washed with H_2O and finally washed with $6N$ H_2SO_4. Calcium is determined by titrating with $KMnO_4$. No residual activity has been observed on the pad.

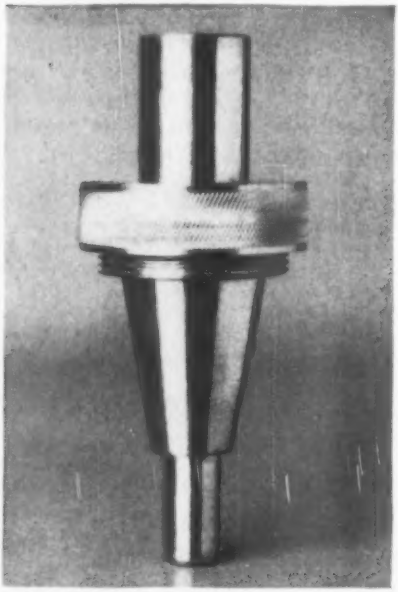


FIG. 1. Assembled filtration unit

Nuclear Reaction Technique Supplements Autoradiography

Ordinary autoradiography fails with some elements because they have no suitable radioisotopes. With a new technique developed by Mats Hillert of the Swedish Institute for Metal Research, Stockholm, Sweden, autoradiographic techniques can be used with nonradioactive elements that can be made to react with external radiation in such a way that secondary radiation is produced.*

The new technique is limited in that the photographic film used to record the secondary radiation must be insensitive to the primary radiation. At present, this dictates the use of neutrons as the primary radiation. In addition, the element to be detected must have a much higher probability of reacting with the primary radiation than have other elements that are present.

The structure of a 98% iron, 2% boron alloy has been investigated as a test of the new technique. Boron has no radioisotopes suitable for autoradiography, but a nuclear reaction radiograph was made by means of the $B^{10}(n,\alpha)Li^7$ reaction. A specimen of the alloy was ground, polished and etched, and a coat of collodion applied. Kodak autoradiographic emulsion was stripped from its backing and allowed to dry on the specimen. The sample was irradiated in a neutron beam from a cyclotron for 16 min.

* Reported in *Nature* **168**, 39 (1951).

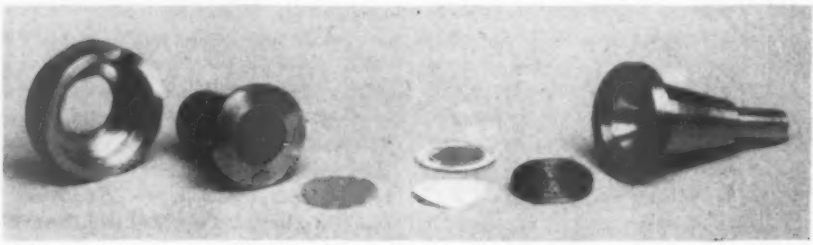


FIG. 2. Disassembled filtration unit

With thermal neutrons, the reaction used has a cross section of 3,000 barns and produces a 1.5-Mev alpha particle. The film used is very sensitive to this radiation.

Results indicate that the method provides good resolution and reproduces the position of the boron quite accurately, as indicated by a comparison of a photomicrograph of the etched metal surface and the film stripped from it.

Studies Prove Transmission Electron Multiplier Feasible

Results of preliminary work on the construction of a transmission-type electron multiplier tube show that a multistage tube could be built which would give a useful gain with a reasonable over-all accelerating voltage. The studies were carried out by Donald R. Cone at the University of California Radiation Laboratory, Berkeley, California.

In a transmission multiplier, the initial electrons are accelerated and focused onto the face of a thin foil with sufficient energy to penetrate the foil and produce secondaries on the far side. These secondaries in turn are accelerated to an adjacent foil where the process is repeated.

Such a tube would have a number of advantages over the conventional electron multiplier: A higher frequency response could be achieved; the tube could be used in a magnetic field; a coaxial output could be provided; and the tube would be nonphotosensitive. But the studies showed that the thin foils that are the heart of the device are extremely fragile, and, with present foils, 3 to 10 kv per stage are necessary to achieve high gains.

The electron gun from a cathode ray tube was used in the preliminary series of experiments. A special chamber was constructed so that the gun could be kept under vacuum when work was being done on the foils under test. In practice, the electron gun would be replaced by a photocathode or other electron source.

For the first test, a beryllium foil about 10 μin. thick was used, and a secondary-to-primary ratio of 1.7 was achieved for 4.6-kv incident electrons. Further tests were conducted with formvar films about 4 μin. thick, with a thin layer of beryllium evaporated on the emergence side. With these foils, ratios of 2.5 were achieved with 3- to 8-kv incident electrons. In both cases the secondary-to-primary ratio was increasing with electron energy, so these figures do not indicate a limit.

TECHNICAL BRIEFS

➤**Film badge** made of cardboard and film has been developed for the Lebanon Township Civil Defense Council (N. J.) by Herbert R. Isenburger of St. John X-Ray Laboratory, Califon, N. J. These monitors will cost less than two cents apiece.

➤**Coloration** of lead-silicate glass caused by gamma radiation has been found to fade in specimens of high-density viewing-window glass tested by R. H. Kernohan and G. M. McCammon at Oak Ridge National Laboratory. The coloration interferes with viewing. Its fading is accelerated by exposure to incandescent light.

➤**Tell-tale clip** for converting Polaroid-Land cameras to emergency radiation detectors has been made available by Polaroid Corp. Clip is permanently installed by owner; unit provides indication of whether dosage falls in 0–1, 1–10, 10–30, or over-30-roentgen range.

➤**Synchrocyclotron** constructed by Philips Industries at the Institute for Nuclear Research, Amsterdam, the Netherlands, has been producing 28-Mev deuterons. A beam current of 20 μa has been achieved.

NUCLEONIC EVENTS

EUROPEANS CONSIDER UNESCO PLAN FOR NUCLEAR PHYSICS LAB

By Ross Hazeltine

McGraw-Hill World News

Paris—European scientists sometimes feel as if they are the poor relatives of their American colleagues. They often lack both funds and modern equipment for advanced research and are dependent on the hospitality of American institutions. This has been especially true in the field of nuclear physics and is a basic reason for the enthusiasm here about a new project proposed by the United Nations Economic, Scientific, and Cultural Organization—the construction of a European Regional Laboratory for Nuclear Physics.

The project is yet hardly more than a gleam in its sponsors' eyes. But scientists of eight nations—Great Britain, France, Italy, Switzerland, Belgium, the Netherlands, Sweden and Norway—met in UNESCO House in Paris last May for the first joint planning talks. And scientific organizations of three nations—France, Italy, and Belgium—contributed a total of $15,000 for preliminary planning.

What the physicists at UNESCO House decided they wanted was pretty much a copy of the Berkeley bevatron. A circular accelerator as big as any in the world, they decided, offered broad possibilities for research without raising any of the political difficulties that would attend construction of a nuclear reactor. They recommended that the laboratory be built around a machine capable of accelerating heavy particles up to at least 3 Bev and possibly up to 6 Bev. They estimated the project completely equipped would cost about $25,000,000 and take about five years to build.

The scientists practically agreed that the laboratory should be built near Geneva, Switzerland, where there is an ample supply of cheap electric power and skilled multilingual technicians. Some of them expressed the hope that the area surrounding the laboratory could be declared international territory to facilitate the movement of men and materials. The UNESCO House meeting also discussed the possibilities of building a betatron or a Van de Graaff in addition to the accelerator but left the final decisions both on the location of the laboratory and on what smaller machines it should include for later planning talks.

So far the idea has been just to accumulate enough information to sell European governments on contributing funds for the construction and operation of the laboratory. UNESCO is sponsoring the initial planning but will step out of the picture once construction gets underway. The laboratory is to be owned and operated jointly by the governments that pay for it.

To Ask Pledges of $200,000

The idea of a joint research institution for nuclear physics will be put before representatives of European governments for the first time at a conference to be called by UNESCO in November. UNESCO will lay before the conference definite proposals for the

organization and financing of the laboratory and will ask the governments to pledge $200,000 for the detailed planning of the project.

The proposals call for a board composed of representatives of all the governments that contribute to the project to exercise top administrative control over the construction and later operation of the laboratory. Under the supervision of this board, the laboratory would be run by a staff of approximately 300, including 25 permanent staff scientists and 50 visiting scientists. It is estimated that annual operating costs will amount to about $1,000,000.

Accelerator Design Plans

If the governments agree to put up the money, the work of designing the laboratory and planning the equipment could begin early next year. Dr. Edouard Regenstreif, a French physicist and engineer on the UNESCO staff, will head the design office. He has been in close touch with American physicists at Berkeley and Brookhaven and plans to leave for the United States after the November conference for a first-hand study of the two U. S. installations.

Dr. Regenstreif will probably stick pretty close to the designs employed at Berkeley and Brookhaven. But he has two new ideas to explore:

First, he intends to investigate the possibility of building a copper, instead of an iron, magnet. He believes copper construction, if it proves to be practical, would allow construction of a much smaller installation of equal power and would reduce building costs considerably.

Second, he will look into the possibility of coupling a small accelerator of about 500 Mev with the cosmotron so that particles would pass first through the small accelerator and enter the larger one at a high initial speed. The small accelerator could be built in a year and used to train technicians until the cosmotron is completed.

European scientists would like the laboratory to have something unique about it.

And it would certainly be a triumph if the European laboratory could develop some entirely new technique—perhaps even draw a few American scientists to Europe for study or research in nuclear physics.

Psychological Factor Noted

The report of the UNESCO House meeting in May emphasized the "psychological" value of the European laboratory. "The danger of normal international interchange of scientists growing into a one-way flow from Europe to America has become a matter of serious concern to a number of European scientific institutions," it said.

The scientists at the UNESCO House meeting included some of Europe's top nuclear physicists—H. Alfven of the Swedish Atomic Energy Commission, E. Amaldi of the Italian National Research Council, E. Capron of the Belgian Interuniversity Institute of Nuclear Physics, O. Dahl of the Norwegian Institute for Atomic Energy, F. K. Goward of the British Atomic Energy Research Establishment at Harwell, F. A. Heyn of the Netherlands Organization for Fundamental Research on Matter, Francis Perrin and L. Kowarski of the French Atomic Energy Commission and P. Preiswerk of the Swiss Atomic Commission.

"The importance for European scientists to have access to a powerful modern cosmotron could hardly be overestimated," they said in their report. "Research workers from different countries would work together, using the same apparatus, helping each other with their problems. The bonds thus established would grow into a permanent collaboration between scien-

tific institutions and industries of the participating countries."

The idea of building a European Laboratory for Nuclear Physics originally came from an American—Isidor I. Rabi, professor of physics at Columbia University. He made the suggestion at Florence, Italy, last year during UNESCO's Fifth General Conference which he attended as a member of the United States delegation.

The success of the venture finally will depend on the governments of the European nations. Each country will have to make a substantial financial contribution in relation to its resources —ranging, perhaps, from something like $1,000,000 a year for France to around $100,000 a year for Norway—in each of the five years construction is in progress. If only a few nations decide to participate, their contributions would have to be increased.

But Prof. Rabi's European colleagues have welcomed his idea and are backing the project enthusiastically. Clearly, they are convinced that such a pooling of financial, scientific and industrial resources is the way to assure that Europe's technical development will keep pace in this era of swift but costly scientific achievement.

ABBOTT LABS OPENS OAK RIDGE BRANCH TO PROCESS ISOTOPES

Abbott Laboratories of North Chicago, Ill., has leased property in Oak Ridge, Tenn., from the Atomic Energy Commission where it will set up facilities to process radioactive isotopes on a commercial basis. The drug firm will establish its Oak Ridge branch across the street from the Oak Ridge Hospital. Remodeling of the building and installation of specialized equipment is already under way, and Abbott plans to begin operation shortly. The firm has been processing radioisotopes for medical diagnosis and therapy at North Chicago since 1946, using isotopes flown from the Oak Ridge nuclear reactor, and supplying radioactive pharmaceuticals to qualified hospitals and cancer clinics (NU, Nov. '50, pp. 4–5).

The move will facilitate more rapid delivery of short-lived isotopes to the ultimate user, because, under the new setup, the time previously needed for flying isotope shipments from the Oak Ridge reactor to North Chicago can be discounted from the process. Irradiated gold, with a 2.7-day half-life, for instance, is meeting increased interest for the treatment of inoperable peritoneal and pleural tumors, and demands for it were a major factor in Abbott's decision to seek an Oak Ridge location.

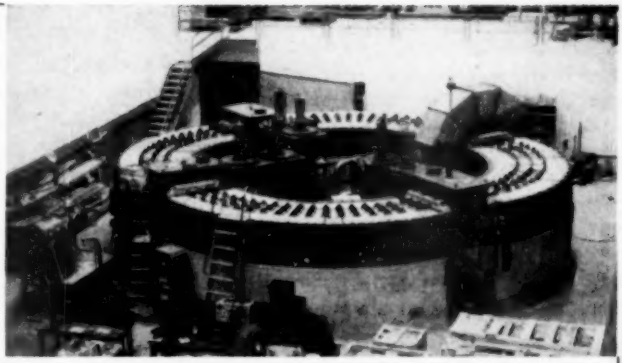
To insure continuity with other Abbott operations, actual handling of orders will still be done in North Chicago, with the majority of shipments being made from Oak Ridge.

AEC HANFORD OFFICE REPORTS ON CONTRACTS

The recently released midyear report of the Hanford Operations Office of the Atomic Energy commission in Richland, Wash., shows that research contracts with a total commitment of $1,172,342 are now in effect between universities and colleges of the Pacific Northwest and the AEC. A total of 38 research projects are in progress.

The University of Washington has eleven contracts worth $764,364; the State College of Washington, eight, $80,988; Oregon State College, six, $80,695; Reed College, five, $103,873; University of Oregon Medical School, four, $69,811, University of Oregon, two, $46,582; University of Wyoming, one, $13,500; and the University of Idaho, one, $12,528.

The University of Washington is involved in a 60-inch-cyclotron program, and a 37-inch cyclotron is under construction at Oregon State College.



Cal Tech's 1-Bev synchrotron shown here is nearing the end of preliminary construction, Phase Zero, and in tests has operated at 1 Mev. During Phase Zero, tests are being made to solve mechanical and electrical problems before assembling the synchrotron in final form. Experimental work will begin with Phase One, expected next winter. Erected on the Institute's campus at Pasadena, Calif., and financed by the Atomic Energy Commission at a cost of $1,250,000, the synchrotron will be the most powerful electron accelerator ever made in this country. It has a 36-foot vacuum chamber, which is surrounded by an iron magnet. As soon as necessary power-supply equipment arrives, engineers will partially dismantle the magnet and install new coils. After gaining experience at half-capacity operation, the Cal Tech physicists and engineers will develop new equipment and make modifications for final assembly, Phase Two

REACTOR SCHOOL EXPANDS EDUCATIONAL RELATIONS PLAN

The Oak Ridge National Laboratory has expanded its program of educational relations and training to include a cooperative setup between the Oak Ridge School of Reactor Technology and various educational institutions interested in introducing nuclear engineering into their curricula.

Under the program there are a limited number of places provided in the School where university faculty members on leave can come and spend part of their time in the reactor research carried out at ORNL and the remaining time as a member of the ORSORT faculty.

The most recent addition to the ORSORT faculty under this arrangement is John R. Agnew, on leave from Purdue University. As a member of the 1951–52 session faculty, he will teach at the School and devote the rest of his time to research in the ORNL Reactor Experimental Engineering Division.

Reginald J. Stephenson, of Wooster College is another professor to join the faculty under this arrangement. He came to the Laboratory a year ago. T. R. Cuykendall, who has since returned to his university post, spent six months at the School on leave from Cornell University in connection with this phase of the program.

IRE PLANS CONFERENCE ON NUCLEAR SCIENCE

A conference of the Professional Group on Nuclear Science of the Institute of Radio Engineers, with the cooperation of the Atomic Energy Commission, will be held at Brookhaven National Laboratory, Upton, N. Y., on December 3–4. Urner Liddel, head of the nuclear physics branch, Office of Naval Research, is

chairman of the program committee.

The program has not yet been completed, but it is planned to have it ready for distribution in the near future. The first day of the conference will be given over to a discussion of AEC problems, and the second day will be devoted to the engineers' replies to the problems.

G.E. REORGANIZES HANFORD DEPARTMENTS

The General Electric Company recently announced that the organization within G.E. which operates the plutonium-producing Hanford Works in Richland will in the future be known as the Nucleonics Division. The announcement came concurrently with the adoption of new, standard company nomenclature and the formation of five staff departments and four line departments within the division.

One of the renamed staff departments is the Radiological Sciences Department, of which Herbert M. Parker is director. It was formerly known as the Health Instrument division.

NPA DELEGATION AMENDED, AEC AUTHORITY EXTENDED

The Atomic Energy Commission's authority to apply DO ratings to orders for materials needed to meet authorized programs for which AEC is the claimant agency was extended recently by the National Production Authority to include the right to allot controlled materials and to redelegate this right to other federal agencies engaged in AEC projects.

NPA amended Delegation 2, which authorizes AEC to apply priority ratings to its orders and to assign this power to others engaged in AEC projects. The amendment brings AEC's activities as a claimant agency in line with provisions of the Control Materials Plan as administered by NPA.

IN BRIEF

➢**Tracerlab, Inc.**, of Boston, Mass, has submitted a proposal to the AEC to investigate the feasibility of operating privately owned radioisotope production and large-scale processing facilities. The study is expected to get under way shortly.

➢***Forestry resources** of the 202,000 acres that comprise the Savannah River plant area of the AEC in South Carolina are under study by the U. S. Department of Agriculture. The AEC wants to find out how it can best use, protect, and manage the forests. Of the total acreage, about 67% is woods.*

➢**An aquatic biology** lab is planned for early construction at the Hanford Works in Richland, Wash. Construction costs are estimated at approximately $375,000.

➢***The Fourth** Annual Conference on Electronic Instrumentation in Nucleonics and Medicine, sponsored by the American Institute of Electrical Engineers, is being planned for January 7–8. It will be held in New York. The planning committee is headed by J. D. Tebo of Bell Laboratories, Inc., with S. Reid Warren, Jr., of the University of Pennsylvania's Moore School of Electrical Engineering, as chairman of the program committee.*

NUCLEAR NEWSMAKERS

Edward U. Condon has resigned his post as director of the National Bureau of Standards to head the research activities of the Corning Glass Works, Corning, N. Y. His resignation becomes effective September 30.

Maj. Gen. Thomas F. Farrell, deputy administrator of the Defense Production Administration, has been appointed assistant general manager for manufac-

turing of the Atomic Energy Commission. General Farrell is on military assignment to the AEC from the Army.

Harold A. Thomas has been advanced to the post of chief of the nucleonic instrumentation section of the National Bureau of Standards' Atomic and Radiation Physics Division.

G. W. Fox is serving as a consultant at Massachusetts Institute of Technology on research for the U. S. Air Force. He is on leave of absence from his position as division chief of physics of the Institute for Atomic Research at Iowa State College.

Donald H. Loughridge has been appointed assistant director of the AEC's Division of Reactor Development. Formerly scientific adviser to the Secretary of Army, Dr. Loughridge will be chiefly concerned with formulating and effecting policies for coordination of technical programs at the Argonne National Laboratory, Chicago, and the Knolls Atomic Power Laboratory, Schenectady. He will also coordinate the operation of the Oak Ridge School of Reactor Technology.

Paul C. Tompkins has been appointed acting scientific director of the U. S. Naval Radiological Defense Laboratory to replace **William H. Sullivan** who resigned recently to take up new work at Oak Ridge National Laboratory. Dr. Tompkins takes on the assignment in addition to his duties as associate scientific director.

Lauriston S. Taylor, who has served as assistant chief of the Atomic and Radiation Physics Division of the National Bureau of Standards, has been named chief of the Division and coordinator of Atomic Energy Commission projects at NBS.

Joseph B. Platt, who served as chief of the physics branch of the AEC's Division of Research since 1949, will this month rejoin the staff of the University of Rochester. He will head up the undergraduate physics program at the Men's College, in addition to carrying on nuclear research.

MEETINGS

International Conference on Nuclear Physics and Fundamental Particles—University of Chicago, Chicago, Ill., Sept. 17–20

Conference on Administration of Research—University of Michigan, Ann Arbor, Mich., Sept. 24–26

Colloquium on Sensitive Emulsions and Their Physical and Physical-Chemical Properties (sponsored by University of Paris, Faculté des Sciences de Paris, and the Centre National de la Recherche Scientifique)—Paris, France, Sept. 24–29

American Roentgen Ray Society—Shoreham Hotel, Washington, D. C., Sept. 25–28

American Society of Mechanical Engineers, Fall Meeting—Hotel Radisson, Minneapolis, Minn., Sept. 25–28

Fourth Conference on Gaseous Electronics (sponsored by APS Division of Electron Physics)—Schenectady, N. Y., Oct. 4–6

American Physical Society (New York State Section)—Rochester, N. Y., Oct. 5–6

39th National Safety Congress & Exposition, National Safety Council—Chicago, Ill., Oct. 8–12

World Metallurgical Congress (sponsored by American Society for Metals)—Detroit, Mich., Oct. 14–19

American Society for Metals, National Metal Congress and Exposition—Fair Grounds, Detroit, Mich., Oct. 15–19

Conference on Building Problems in Connection with Utilization of Nuclear Energy (arranged by American Institute of Architects, sponsored by AEC and NRC)—National Research Council, Washington, D. C., Oct. 22–23

National Electronics Conference—Chicago, Ill., Oct. 22–24

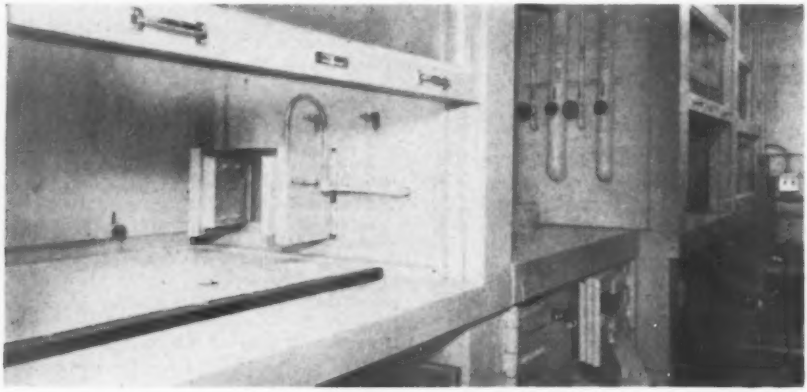
American Institute of Physics in joint meeting with Founding Societies of the Institute (American Physical Society; Optical Society of America; Acoustical Society of America; Society of Rheology; American Association of Physics Teachers; also American Crystallographic Association)—Hotel Sherman, Chicago, Ill., Oct. 23–27

American Physical Society in joint meeting with American Institute of Physics—Chicago, Ill., Oct. 25–27

Institute of Mathematical Statistics—Washington, D. C., Oct. 26–27

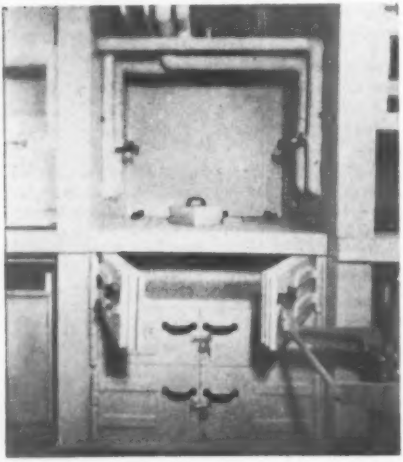
American Mathematical Society—Washington, D. C., Oct. 27

PRODUCTS and MATERIALS



A SHIELDED LABORATORY FOR RADIOACTIVITY STUDIES

The recently completed isotope laboratory in the Biology Department of Brookhaven National Laboratory has been specially designed and constructed to provide shielded working and storage spaces. Four hoods have been installed in which plants can grow under carefully controlled light and temperature conditions while being exposed to a radioactive source inside.



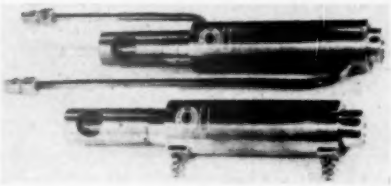
The hood shown above is 3.5 ft deep and 8 ft long. The subsurface top is 3-in. steel plate to shield workers' legs and feet. The exposed sides are laminated with a 2-in. lead and two ¼-in. steel plates. A lead and steel door opens directly into the storage cave for transfer of radioactive materials.

The storage cave shown at left, situated between two of the hoods, consists of six steel doors, each 3 in. thick, behind which radioisotopes are stored. The doors move on heavy ball bearing strap hinges; the joining edges are stepped. The top shelf is 4 in. of solid steel. In this top are eight solid steel plugs, each 4 in. thick and 9 in. square, which cover pipes that extend into the ground about 20 ft for storage of high-

activity materials. The space surrounding these pipes and the walls of the storage space is filled with solid, dense concrete. Air, hot and cold water, and gas services can be operated from the storage area.

Lead-lined cabinets, 12 ft long, 8 ft high, and 18 in. deep, are also provided for storage of radioactive materials.

Design and fabrication of the laboratory was by Bar-Ray Products, Inc., 209 25th St., Brooklyn, N. Y.

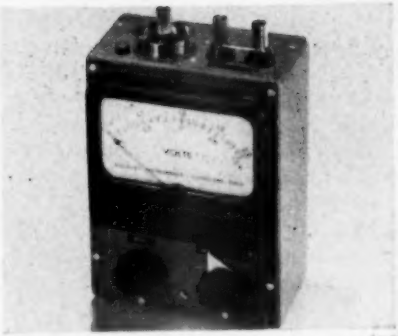


WATER-COOLED COUNTERS

N. Wood Counter Laboratory, 5646 Harper Ave., Chicago 37, Ill. The type HG neutron counter is filled with BF_3 enriched with B^{10}. It is enclosed in a water-cooled jacket so that it may be used at high temperatures. The type HD self-quenching gamma counter uses the same water-cooled construction. Two types of jackets are available, one requiring plastic tubing and the other copper or plastic tubing.

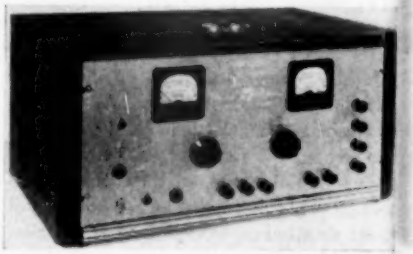
RADIOACTIVITY SLIDE RULE

J. L. Herson, 3000 Connecticut Ave., N. W., Washington 8, D. C. With this slide rule, present activity can be found if the half life and the activity at some previous time are known. A set of scales is also provided for finding the activity at some previous time if the half life and present activity are known. With knowledge of the activity at two times, the half life can be found. A set of conventional multiplication scales is also provided.



ELECTROMETER

Keithley Instruments, 1507 Warrensville Center Rd., Cleveland 21, O. The model 200 vacuum-tube electrometer has an accuracy of 1% at full-scale reading; accuracy of low-scale readings is held to within 5% of reading, according to the manufacturer. This self-contained d-c voltmeter has an extremely high input impedance; in conjunction with a known resistance it is capable of measuring currents as low as 10^{-14} amperes.



POWER SUPPLY

Universal Electronics Co., 2012 So. Sepulveda Blvd., Los Angeles 25, Cal. The model 100A combines three power supplies in a single cabinet. The B supply is continuously variable in the range 0–325 volts, d-c, and delivers 0–200 ma. Variation is said to be less than 0.2 volts from no load to full load, or for line fluctuations from 105 to 125

volts. Either positive or negative connection may be made. The bias supply gives a maximum of 2 ma in the range 0–150 volts. Hum voltage is said to be within 2 mv, rms, for any voltage or load within ratings. Two independent a-c outputs are provided to give either 12.6 volts at 3 amperes or 6.3 volts at 6 amperes. Internal impedance is less than 1 ohm, d-c, and less than 0.2 ohm from 20 cycles to 50 kilocycles.

DEACTIVATOR FILTER

Atomic Associates, Inc., Land Title Bldg., Philadelphia 10, Pa. The model B deactivator is a combined filter and ion exchanger for removal of such isotopes as I^{131}, Na^{24}, and P^{32} from solutions. It is claimed that the device will treat as much as 500 gallons of solution before being used up; unused capacity can be seen by direct view.

PLASTIC COATING

Plastic Cement and Chemical Co., 340 E. 27th St., New York 16, N. Y. This thermosetting resin, called Fenolic 101, cures at room temperatures. It is said to be extremely resistant to high temperatures, acids, and abrasion. It can be applied by any of the usual methods to any uncoated wood or composition surface.

TIME-INTERVAL METER

Berkeley Scientific Co., Sixth and Nevin Aves., Richmond, Cal. The model 510 is a direct-reading instrument that measures the elapsed time between any two events in the range from 10 μsec to 1 sec. The stop and start channels can be triggered by signals having a minimum peak voltage of 1 volt, positive or negative, and a rate of rise of not less than 1,000 volts/msec. A sensitivity control is provided for selection of minimum amplitude of the input pulses. Accuracy of the instrument is said to be ± 10 μsec; short-term stability is 1 part in 10^5. An accessory socket provides 2 amperes at 6.3 volts, a-c, and +300 volts, d-c, regulated. Modifications are available for measurement of the duration of a single pulse, for extending the range of the instrument to as much as 10^6 sec, and for using the instrument as a straightforward counter at rates up to 10^5 events per second.

LITERATURE AVAILABLE

Air Filters. Catalog illustrates and gives data on electric air filters. *Trion, Inc., 1000 Island Ave., McKees Rocks, Pa.*

Blast Cleaner. Illustrated brochure shows uses and accessories of this cleaner. *Vacu-Blast Co., Inc., 350 Peninsular Ave., San Mateo, Cal.*

Apparatus. Bulletins describe line of radioactivity detection and measurement equipment. *The Radiac Co., 489 Fifth Ave, New York 17, N. Y.*

Counter Tubes. Catalog 51T describes and gives data on counter tubes and accessories available. *Anton Electronics Laboratories, Inc., 1226 Flushing Ave., Brooklyn 6, N. Y.*

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as research in the physical sciences, control of radiation hazards, and biological and medical research have been covered.

These program reports have always been extremely interesting in providing an over-all picture. The task of compiling and correlating the information from the far-flung AEC laboratories has no doubt been a difficult one. AEC's information division is to be complimented on a job well done.

The one major subject which has not been touched on in more than cursory fashion is the reactor development program. A report on this was promised in the fifth semiannual report. However, differences of opinion on what can and should be said have held it back. This could be one of the most interesting of the semiannual reports.

2. The second "sign of our times" in the tenth report is the description of AEC's change in philosophy in supporting unclassified basic research.

This change relates basic research more directly to the needs of the program. AEC is doing this by working through scientists who have been investigated and cleared. The Commission informs them "of research work in AEC laboratories and encourages them to use this knowledge, and their access to secret material, as guidance in selecting areas for their own research and in giving direction to other unclassified work in their institutions."

This is a basic and necessary change in policy. It will be interesting to see how such direction affects the results of basic research. —*J.D.L.*

Random Notes *(Continued from page 5)*

The lead item on gamma-ray radiography is an example of the speed with which C. S. items can be published. This came to us via our contact at Harwell, England. He said the method proposed in the note had been described at the Oxford isotope technique conference in mid-July. He said it aroused widespread interest and that he felt it warranted immediate publication. We looked at it and agreed with him. And within five weeks of receipt of it, we have it out in print in this issue. In some cases we can publish within four weeks.

The second item, a Ca^{45} measurement device, came to us as a result of a visit made to the Ottawa laboratory of the authors. They hadn't thought of publishing it because we had published something similar previously. However, the device was actually different and they found it useful. On this basis, we requested that they submit it to us.

The note on the new autoradiography technique appeared in Nature, *the British publication. We learned recently, as the indirect result of a readership survey, that few of our readers read* Nature *regularly. Therefore, we felt it worthwhile to give a brief description of the technique.*

We took the last item on the transmission multiplier from a University of California technical report. It looked interesting to us and we obtained the author's O.K. to run a brief summary of his lengthy report.

And that's this month's C. S. department. We are expending considerable effort to bring items in; however, the success of the section depends on readers' contributions to it. —*J.D.L.*

NEW α, β, AND γ *Proportional Counter*

SELECTIVE α, β, AND γ COUNTING • 2 π GEOMETRY • NO WINDOW ABSORPTION • AUTOMATIC PREFLUSH • NO "TUBE AGING" • NEGLIGIBLE COINCIDENCE LOSS • COUNTING RATE LIMITED ONLY BY SCALER • NO SPURIOUS PULSES • LOW BACKGROUND • ADAPTABLE TO GEIGER AS WELL AS PROPORTIONAL COUNTING

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The absence of spurious pulses and negligible coincidence loss even at very high counting rates, which are inherent advantages of counting in the proportional region, combine with the absence of window absorption, the highly reliable pulse amplification, and the low background of this counter to make this unit one of the most useful in the field of radioactivity measurement.

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BOOKS

BOOKS RECEIVED

Labelled Atoms, by Raymond Glascock, Interscience Publishers, Inc., New York (No. 18 in Sigma Introduction to Science Series; Sigma Books, Ltd., London), 1951, 227 pages, $1.25. This is an elementary treatment of the subject of radioactive tracers and some of the instruments used in their connection. Suitable for high-school science majors, college freshmen and sophomores, and others seeking an insight into this science, the text is well illustrated with simple sketches, autoradiographs, and the like. The references given at the end of each chapter are, in general, to early literature. In addition to chapters on tracers in medicine, biology, agriculture, and botany, the author also touches on the preparation and properties of tracer isotopes.

A Concise History of Astronomy, by Peter Doig, Philosophical Library, New York, 1951, xi + 320 pages, $4.75. A book for the general reader, giving the main events and notes on the chief work of individual astronomers, written by the editor of the *Journal of the British Astronomical Association*, with a foreword by Sir Harold Spencer Jones, Astronomer Royal.

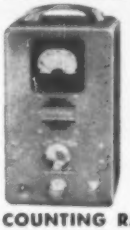
OTHER LITERATURE

Major Activities in the Atomic Energy Programs, January–June, 1951. This is the GPO reprint of the Atomic Energy Commission's Tenth Semiannual Report (151 pages) submitted to Congress in July, 1951. *Available from Superintendent of Documents, U. S. Govt. Printing Office, Washington 25, D. C., $0.35.*

For Your Nuclear Laboratory

BASIC SCALER Model 100 was designed for the express purpose of providing an easy-to-operate scaling circuit of the *finest quality* at *minimum cost*, and in such form that additional facilities could be added from time to time to meet the increasing requirements of the user. In one compact unit this instrument combines a *direct reading electronic scale of 100*, mechanical register for *extended range* and a *regulated high voltage power supply*. An *accessory socket* permits full use of such auxiliary equipment as automatic clock, predetermined timers, extended range unit for predetermined count, loud speaker, count rate meter and count rate computer. Dimensions: 14½" x 9¾" x 10¾". Wt. 18 lbs.

UTILITY SCALER Model 110 includes all of the features of the Model 100 plus additional facilities which make it a universal laboratory instrument for nuclear work. The power supply can, by simple adjustment, be made to provide either *positive* or *negative high voltage*, thus making it suitable for use with either *Geiger Muller or Scintillation detectors*. A built-in preset-count mechanism provides scaling factors of 100, 200 and 400 and *automatic predetermined counts* of 1000, 2000, 4000, 10,000 and 20,000. *Accessory plug* and convenience outlet at the rear chassis of the Scaler which provide for unit, counting rate computer, preamplifier and other auxiliary devices. Dimensions: 14½" x 9¾" x 10¾". Weight: 18 lbs.



LABORATORY MONITOR Model 1800 is a general purpose count rate meter with provision for *visual and aural indication*. Panel switch permits selection of five different meter ranges (300 cpm., 900 cpm., 3000 cpm., 30,000 cpm.) Meter is *self zeroing* and does not require calibration. A single control is provided for "On-Off" and volume control of aural section. Monitor is supplied complete with GM tube and probe. Dimensions: 6½" x 6½" x 10½". Weight: 8 pounds.

COUNTING RATE METER Model 1810, is a complete general purpose laboratory instrument, with provision for panel switch selection of *10 different counting rate ranges* and 8 *different response half-time factors*. For each position of the "Range" switch both range in counts per minute and the deviation in counts per minute may be *read directly* on the instrument panel. For each position of the "Response ½-time" switch both response half-time in seconds and the deviation multiplier for that particular response time may be *read directly* on the instrument panel. Thus it is possible to *select* absolute *optimum operating conditions* for any given circumstance. A zero meter check and a 7200 count per minute calibration are also provided. Unit includes regulated high voltage and low voltage supplies. Dimensions: 14½" x 9¾" x 10¾". Weight: 20 pounds.

For data sheets and prices, please write Dep't. N

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The Juno Survey Meter measures the intensity of, and distinguishes between alpha, beta, and gamma radiation. Its use protects personnel from over-exposure to radioactivity and X-rays. Two models are available: SRJ-1 for standard range (50, 500, and 5000 MR/HR full scale). HRJ-1 for high range (250, 2500, and 25,000 MR/HR full scale). For complete details, write for Bulletin No. 125.

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An Extrapolation Chamber: Construction and Use (*Continued from page 43*)

and lead collecting electrodes was less.

Usefulness. In our experience, the primary usefulness of the variable pressure chamber is for measurements in which it is desirable, or necessary, to control the pressure or composition of the gas in the chamber.

In making dose-rate measurements, the pressure chamber permits working with a gas of controlled purity, permits the use of lower intensities of radiation, and minimizes difficulties due to dust and lint between the electrodes. On the other hand, the pressure chamber is less convenient because of the poor accessibility of the interior.

In some cases, caution must be exercised to prevent contamination of the chamber and vacuum system, since a source deposited on a thin holder may be agitated and removed during the first part of the pumping process.

By unbolting the pressure chamber, it can be detached, and the extrapolation chamber used in the conventional manner.

BIBLIOGRAPHY

1. G. Failla. The measurement of tissue dose, *Radiology* **29,** 202 (1937).
2. G. Failla, H. Rossi, R. Clark, N. Bailey. The measurement of tissue dose of ionizing radiation, AECD-2142 (1947).
3. C. W. Sheppard, R. K. Abele. Construction and calibration of equipment for measuring the surface exposure of phosphorus-bakelite beta ray source, ORNL-265, AECU-655 (1949)
4. K. Z. Morgan. The use of the roentgen equivalent physical (rep), ORNL-783 (1950)
5. H. M. Parker. Tentative dose units for mixed radiation, *Radiology* **54,** 2 (1950)

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GT-10	Immersion or General Beta Counter	142	18	60	1100	220	0.06	13
GT-11	Immersion or General Beta Counter	202	18	120	1100	220	0.05	26
MRC-1	Powder or Liquid Beta Counter	190	24	60	1100	220	0.06	11
MRC-2	Powder or Liquid Beta Counter	250	24	120	1100	220	0.05	22
GT-21	Gamma Counter	310	38	220	1100	220	0.05	80

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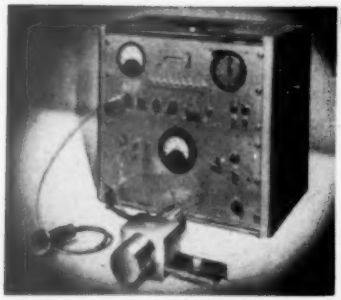

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	Company A RCL	Company B	Company C	Company D
1. Complete, ready to plug-in and count	Yes	No	No	No
2. Count soft beta particles	Yes	Yes[1]	Yes[1]	Yes[1]
3. Count hard beta particles	Yes	Yes[1]	Yes[1]	Yes[1]
4. Count gammas rays	Yes	Yes[1]	Yes[1]	Yes[1]
5. Count alpha particles	Yes	Yes[1]	Yes[1]	Yes[1]
6. Facilities for neutron counting (60 cm. BF_3)	Yes	No[2]	No[2]	No[2]
7. Facilities for G-M mica window counting	Yes	Yes	Yes	Yes
8. Facilities for flow counter	Yes	Yes	Yes	Yes
for methane	Yes	No	No	No
for argon – methane	Yes	Yes	Yes	Yes
for helium – isobutane	Yes	Yes	Yes	Yes
9. Facilities for scintillation counting	Yes	Yes	Yes	Yes
10. "Panel-mounted" gas line control valves, connections, bubbler, etc.	Yes	No	No	No
11. Cabinet with Hammertone finish, for easy decontamination	Yes	Yes	No	No
12. Copper-plated cabinet	Yes	No	No	No
13. Stainless steel hardware used throughout	Yes	No	No	No
14. Built in register	Yes	Yes	Yes	Yes
15. Built in timer	Yes	Yes	Yes	Yes
16. Preset count	Yes[3]	Yes	No	Yes
17. Preset time	Yes[3]	Yes	No	Yes
18. Scaling factor adjustable	Yes	Yes	No	No
19. Scaling factor of 512 or greater	Yes	No	No	Yes
20. 4⅜" High voltage meter	Yes	No	Yes	Yes
21. High voltage range of 400 to 5,000 volts regulated	Yes	No	No	No
22. Four stage, direct-coupled amplifier for high voltage regulation	Yes	No	No	No
23. Special circuit for correction of "Nonlinearity" in high voltage circuit	Yes	No	No	No
24. Independent cathode follower stage for oscilloscope connections	Yes	No	No	No
25. Electrostatic shielded transformers	Yes	No	No	Yes
26. 500 μamp meter, ± 1% accuracy used in high voltage circuit	Yes	No	No	Yes

[1] with attachment. [2] requires 3,000 – 4,000 volts. [3] on request.

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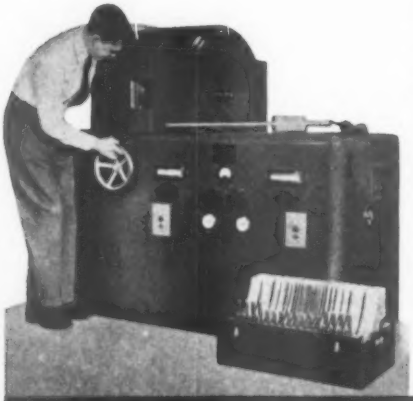

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and
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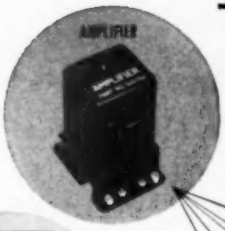
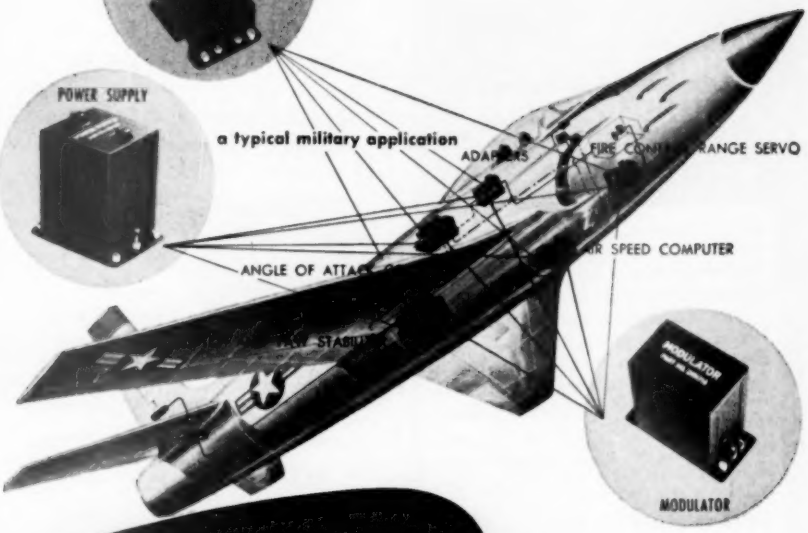


a typical military application



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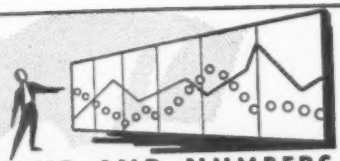

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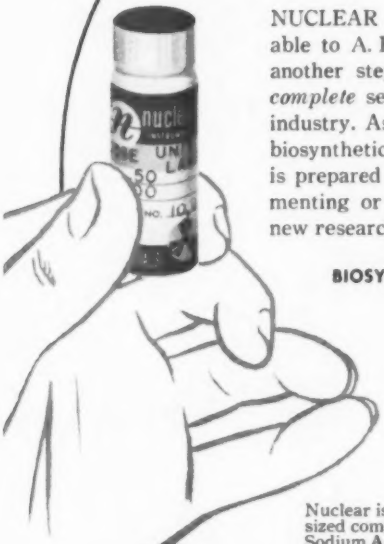

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